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Simulator Evaluation of the Effects of Reduced Spoiler and Thrust Authority on a Decoupled Longitudinal Control System During Landings in Wind Shear

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SUMMARY

The effect of reduced control authority, both in symmetric spoiler travel and thrust level, on the effectiveness of a decoupled longitudinal control system is examined during the approach and landing of the NASA Terminal Configured Vehicle (TCV) Aft Flight Deck Simulator in the presence of wind shear. The evaluation was conducted in a fixed-base simulator that represented the TCV aft cockpit. The piloting task was to capture and maintain a 3° glide slope by using the electronic attitude-direction indicator (EADI) and to complete the landing by using that display's perspective runway.

There were no statistically significant effects of reduced spoiler and thrust authority on pilot performance during approach and landing. Increased wind severity degraded approach and landing performance by an amount that was often significant. However, every attempted landing was completed safely regardless of the wind severity. There were statistically significant differences in performance between subjects, but the differences were generally restricted to the control wheel and control-column activity during the approach.

INTRODUCTION

A fixed-base simulation study (ref. 1) reported the beneficial effect of decoupled longitudinal controls during the approach and landing of the NASA Terminal Configured Vehicle (TCV) Aft Flight Deck Simulator in the presence of severe wind shear. The primary piloting task of that study was to capture and maintain a 3° glide slope by using the advanced avionics display (ref. 2) of the simulated TCV. The display included flight-path angle and track symbolism in addition to a perspective runway that enabled landings to be completed without the use of simulated visual cues from outside the airplane. The decoupled control system automatically changed the thrust, elevator position, and symmetric spoilers to produce steady-state decoupling of flight-path angle, pitch angle, and forward velocity. The decoupled control system demonstrated improved approach and landing performance in severe wind shear over the velocity control-wheel steering (VCWS) system that is the base-line control system for the TCV. By using a pilot-rating scale, the pilots rated the approach and landing task as much as 3 to 4 increments better than use of the VCWS system.

The present simulation study examines the effect of reduced spoiler and thrust authority on decoupled-control performance in wind shear. The decoupled-control system studied in reference 1 employed full spoiler authority because a specific design for operating the TCV spoilers in a direct lift control (DLC) mode did not exist at that time. A preliminary design study for driving the TCV spoilers symmetrically for DLC has now been completed that restricts the maximum spoiler deflection to 16°. The present simulation study includes this 16° spoiler limit. The maximum thrust level was also reduced approximately 6.7 percent to correspond to the maximum thrust level currently being used by the VCWS auto throttle, in order to make the comparison with that system more meaningful. The study was performed to determine whether this reduced control authority would have a significant effect on the decoupled control-system performance in wind shear. The study was conducted in the simulated aft cockpit of the TCV previously used in reference 1.

The use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

SYMBOLS

a_z	normal acceleration, g units (1g = 9.8 m/sec^2)
F	calculated test statistic, dimensionless
G	matrix of prefilter gains used in decoupled controller
g	acceleration due to gravity, m/sec^2
H	matrix of feedback gains used in decoupled controller
h	altitude, m
I_X, I_Y, I_Z	moments of inertia about X, Y, and Z body axes, respectively, kg-m^2
I_{XZ}	product of inertia, kg-m^2
T	total thrust, N
t( )	statistical quantity of t-test of students' t-distribution; parentheses designate particular factor considered
u	forward velocity
V_{GS}	ground speed, knots
X,Y,Z	body axes
α	angle of attack, rad or deg
γ	inertial flight-path angle, rad or deg
$\Delta\gamma$	deviation in flight-path angle from 3° reference condition, deg
δ_{col}	column deflection, m
δ_e	elevator deflection, positive for trailing edge down, rad or deg
δ_{sp}	spoiler deflection, rad or deg
δ_{th}	equivalent throttle deflection
δ_{wh}	control-wheel deflection
θ	pitch angle, rad or deg

Subscripts:

c commanded by pilot

cr critical

Abbreviations:

AFD aft flight deck

ANOV analysis of variance

DLC direct lift control

DMR( ) statistical quantity of Duncan multiple-range test; parentheses designate particular factor considered

ΔIAS deviation in indicated airspeed from reference condition (normally 122 knots but was 130 knots for decoupled controls in severe turbulence)

d.o.f. degrees of freedom

EADI electronic attitude-direction indicator

EHSI electronic horizontal-situation indicator

ELOC localizer error

GSE glide-slope error

IAS indicated airspeed

MLS microwave landing system

NCDU navigation control-display unit

PMCC panel-mounted control column

PMCW panel-mounted control wheel

rms root mean square

TCV NASA Terminal Configured Vehicle Aft Flight Deck Simulator

VCWS velocity-vector control-wheel steering

A dot over a symbol denotes differentiation with respect to time.

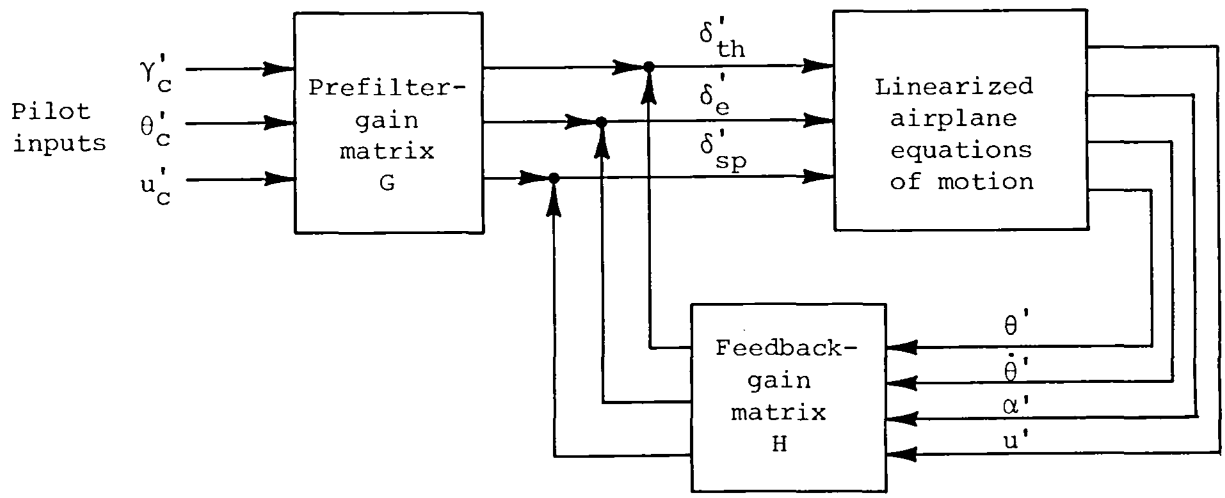
A prime denotes nondimensional perturbations from equilibrium.

SIMULATED AIRPLANE

The simulated TCV airplane was a Boeing 737-100 medium jet transport (fig. 1) generated by the real time solution of the nonlinear equations of motion for six rigid-body degrees of freedom. The simulation included detailed response characteristics of the Pratt & Whitney JT8D-9 turbofan engines, nonlinear actuator models, and microwave-landing-system (MLS) sensor models. The physical characteristics of the airplane are presented in table I, and the initial conditions for the simulation are given in table II. The two-man aft flight deck (AFD) is shown in figure 2 and includes panel-mounted controllers for pitch and roll control. The panel-mounted control column (PMCC) employed a 2.54-mm deadband and had a maximum deflection of ±6.3 cm. The panel-mounted control wheel (PMCW) had full-scale deflections of ±30° and operated in a velocity-control mode in which the airplane roll attitude was held constant after the control force was released when the bank angle was greater than 5° at control release. When the bank angle was less than 5° at control release, the control system attempted to hold the present ground track of the airplane by modulating bank angle. A detailed description of the velocity-control mode for the roll axis is given in reference 2.

Decoupled Control System

The general approach taken for providing independent or decoupled control of flight-path angle, pitch angle, and forward velocity is depicted in the following sketch:



The decoupled control system was applied to the longitudinal mode and was mechanized so that the pilot commanded flight-path angle γ_c' through inputs to the column, pitch angle θ_c' through the speed-brake handle, and forward velocity u_c' through the throttle. In addition, the thumb controller on the left horn of the control yoke could be used to trim commanded flight-path angle at a constant rate of 1 deg/sec. The decoupled controller was a closed-loop control system that required continuous measurement of pitch angle, pitch rate, angle of attack, and forward velocity.

Use of the feedback-gain matrix H and prefilter-gain matrix G resulted in the throttle δ_{th}', elevator δ_e', and spoilers δ_{sp}' moving to produce steady-state decoupled control of flight-path angle, pitch angle, and forward velocity as commanded by the pilot. Spoiler panels 2, 3, 6, and 7 (fig. 1) were deployed asymmetrically for roll control and symmetrically for longitudinal control when the decoupled controls were used. The most versatile means for obtaining G and H is the use of an onboard computer to find the time-varying adaptive gains. However, the simplified approach used in reference 1 was also used in the present investigation where the use of the controller was restricted to the approach and landing phase of operations. Consequently, constant prefilter and feedback gains (calculated for the conditions in table II) could be used so that in an actual airplane no onboard computation would be necessary. The present investigation uses the same gains that were used in reference 1. A detailed development of the decoupled control system may be seen in reference 1. The prefilter-gain matrix is given as

$$G = \begin{bmatrix} 3.9304 & 9.6802 & 8.0530 \\ -0.8772 & 1.5967 & -1.8829 \\ -8.0800 & 3.8552 & 11.6078 \end{bmatrix}$$

and the feedback-gain matrix is given as

$$H = \begin{bmatrix} 1.1336 & 16.9936 & 0.0606 & 5.4089 \\ -3.1518 & -31.1558 & 0.6122 & 0.6983 \\ 3.3400 & 42.7517 & 0.8662 & -0.6189 \end{bmatrix}$$

Primary-Display System

The primary display used during the simulated approach and landing was the electronic attitude-direction indicator (EADI) shown in figure 3. The essential features for longitudinal control included a glide-slope indicator, commanded and inertial flight-path angle or "gamma wedges," an artificial horizon, and an attitude reference scale. The attitude scale was also used to obtain the magnitude of the commanded and inertial flight-path angles. The display contained a roll indicator, a localizer indicator, and a relative track indicator. The relative track angle was the inertially referenced track of the airplane relative to the runway heading. The track angle, which was indicated by a tab that moved along a line parallel to the artificial horizon line, was measured by using a scale drawn on the horizon line in 10° increments referenced to the runway heading. Also included on the display was a perspective runway drawn on a 30° by 40° field of view. The perspective runway consisted of the outline of a runway with an extended center line beginning 1 n. mi. before runway threshold and extending to the horizon. In addition, four lines were drawn perpendicular to the runway center line at intervals of 304.8 m, beginning 304.8 m beyond the runway threshold. The runway symbol represented a 3048-m runway approximately 46 m wide.

TEST PROGRAM

The subjects' task was to assume command in level flight and use the glide-slope deviation and flight-path-angle indicators to capture and maintain the desired 3°

glide slope in the presence of wind shear. The commanded airspeed was set at the desired touchdown value of 122 knots shortly after flight initiation in light and moderate wind shear. When the turbulence level was high, as in severe wind shear, the subjects generally maintained 130 knots until just before touchdown. The pitch attitude was nominally set at 3° at the beginning of each run to keep the nose wheel off the ground at touchdown. The decoupled control system attempted to maintain the commanded pitch attitude and airspeed without further pilot attention as the flight progressed, thus enabling the subject to concentrate on controlling flight-path angle. When the MLS beam was intercepted, the subjects' trimmed the airplane onto the desired 3° descent path by using the trim button on the control yoke. They then used either the trim button or the column to make any necessary changes in flight-path angle. The subjects used the perspective runway to complete the landings nominally 304.8 m down the runway from the threshold.

The wind-hazard data used in this study and in reference 1 were produced for the Federal Aviation Administration (FAA). (See ref. 3.) The wind profiles are modeled in the TCV simulator in terms of three-axis mean wind specifications and Dryden turbulence specifications. The six wind-shear profiles used in this study and in reference 1 are presented in figures 4 to 9. The corresponding gust intensities are shown in tables III and IV. A brief description of the six wind-shear profiles is presented in the following table:

Wind-shear profiles	Description
B2	Low-intensity wind shear; little turbulence
B3	Low-intensity wind shear; little turbulence
B6	Moderate wind shear
B7	Moderate wind shear; turbulence with rms gust intensities up to 8 knots
D3	Very severe wind shear; turbulence with rms gust intensities up to 8 knots
D10	Very severe wind shear; reconstruction of wind shear during 1975 Eastern Airlines crash at John F. Kennedy International Airport; turbulence with rms gust intensities up to 8 knots

RESULTS AND DISCUSSION

The purpose of the present study was to determine whether reduced spoiler authority and thrust level would have a significant effect on the performance of the decoupled control system. Six flights were performed in each wind condition (light, moderate, and severe) with limited authority and with full authority. The single subject used in this study, a research engineer henceforth referred to as subject D, was not one of the three subjects used in reference 1. Consequently, it was also necessary to show that his performance with unlimited authority was not significantly different from that of the three research pilots used in reference 1. A detailed statistical analysis comparing subjects and control authority is presented in the appendix. The data from the three research pilots A, B, and C of reference 1 are also included in the appendix.

General Analysis

A typical time history of a flight performed by subject D with unlimited spoiler authority in severe D10 wind (Kennedy type) is presented in figure 10. The decoupled control system kept the airspeed from falling below 115 knots, and the angle of attack was generally less than 10°. However, the spoilers exceeded 16° for several seconds at three points in the flight. For comparison, a typical flight performed by subject D with limited spoiler and thrust authority is presented in figure 11. The angle of attack was still generally less than 10° which was approximately 2 1/2° below the angle at which stick shaker activity would normally commence. In addition, airspeed was maintained well above the 96-knot stall speed. The spoilers were either fully retracted or were extended to the 16° limits for long periods of time during the flight. However, limited spoiler authority did not seriously compromise the decoupled control system because pitch attitude remained very close to the commanded 3° value prior to 120 sec. In particular, pitch attitude was approximately 3° between 80 and 110 sec (and angle of attack and forward velocity were the appropriate values) even though the spoilers were fully retracted. By contrast, when the spoilers were fully retracted between 120 and 140 sec decoupling was compromised and the pitch attitude diverged to almost 7°. This divergence was attributed to thrust limiting that occurred during this time period. Subject D was always able to complete the landings and generally was unable to detect that the controls were limited.

The airplane is no longer decoupled when the spoilers are limited, and the inertial gamma wedges of the EADI (fig. 3) will not overlay the commanded gamma wedges but will stand off, sometimes for several seconds. The sustained separation of the gamma wedges due to spoiler saturation is difficult to detect because the gamma wedges sometimes remain separated for several seconds, even when the spoilers are not saturated. The time history of a typical flight performed with limited spoiler authority in severe D3 wind shear (similar to Kennedy type but without the vertical wind component) is presented in figure 12. The spoilers were generally not saturated in this wind shear. Specifically, between 40 sec and 60 sec into the flight the spoilers never were fully retracted or extended. However, the commanded flight-path angle was 2.5° in that time period while the inertial flight-path angle was always greater than 2.5°. Thus, the gamma wedges were separated for some 20 seconds even though the spoilers were not limited and the airplane was decoupled.

A typical flight performed in light B3 wind shear is presented in figure 13 to illustrate the effect of the 16° spoiler limit on decoupled control capability. Between the 15-sec point and the 25-sec point the spoilers were just at the 16° limit. In this time period, the commanded flight-path angle was -5° and the steady-state value of inertial flight-path angle was also -5°, so the airplane remained decoupled for flight-path angles as large as -5°. Of course, flight-path angles up to almost ±8° could be attained. However, the airplane would be decoupled only up to approximately ±5° and the airplane would deviate from the commanded 3° pitch angle for larger flight-path angles.

Statistical Analysis

Approach performance.- The approach-performance data for this study are presented for an early portion of the approach and two later portions. The first portion includes rms values from data taken every 31.25 msec between altitudes of 457.2 m and 228.0 m. The performance parameters considered (fig. 14) were flight-path-angle error, glide-slope error, indicated-airspeed error, localizer error, and the control inputs to the panel-mounted control wheel and control column. Each symbol denotes the mean value of six flights performed by each subject under each wind condition. Subject D made larger errors in flight-path angle when flying in severe winds than did the other three subjects. However, the difference was not statistically significant (see appendix), and there was no difference due to limited control authority. Subject D had smaller glide-slope errors in severe winds than did the other subjects. The difference was not statistically significant, however, nor was the difference associated with the levels of control authority. The deviation in indicated airspeed showed no subject or control-authority effects. Subject D made larger localizer errors in all winds than did the other subjects. The difference was statistically significant only in light winds where subject D with unlimited authority had larger errors than did the other three subjects. The difference in localizer error associated with limited authority was not statistically significant. Subject B used larger control-wheel inputs than any of the other subjects, and the difference was statistically significant in moderate and severe winds. There were no consistent subject effects on control-column activity. In summary, there was little effect of subjects and no effect of control authority during the initial portion of the approach. Increased wind severity, however, degraded all performance parameters except localizer error, and the degradation was often statistically significant.

The approach-performance parameters for the intermediate portion of the approach, between altitudes of 76.2 m and 30.5 m, are shown in figure 15. Flight-path-angle error, glide-slope error, and indicated-airspeed error show no statistically significant effect (see appendix) of subjects or control authority. The localizer error, a lateral-control parameter, showed significant subject effects in that subject D made larger errors in moderate and severe winds than did the other three subjects. However, subject D with limited control authority did not make larger errors than the other three subjects with unlimited control authority. Subject B again used significantly larger control-wheel inputs in light and moderate winds than did the other subjects. Subject D used larger control-column inputs in all winds than did the other three subjects, and in severe winds the difference was statistically significant. However, subject D used significantly smaller control-column inputs when he had limited control authority than when he had unlimited authority. Consequently, the use of limited control authority did not degrade performance in any of the six approach-performance parameters although there was some variation in performance between subjects. Increased wind severity again degraded all of the performance parameters and the difference was often statistically significant.

The approach-performance parameters for the final portion of the approach, between altitudes of 30.5 m and 15.1 m, are shown in figure 16. Subject D generally made smaller errors in flight-path angle and indicated airspeed than the other three subjects, but the difference was not statistically significant nor was the effect of limited control authority. Glide-slope error and localizer error showed no consistent effects of subjects or control authority. Subject B again made significantly larger control-wheel inputs in light and moderate winds than the other subjects. In addition, in severe winds subject D made significantly larger control-wheel inputs with unlimited authority than he did with limited authority as well as significantly larger inputs than subject C. Subject D made larger control-column inputs in all wind conditions than did the other subjects, primarily because he concentrated more on the glide-slope error than the other subjects. The differences in control-column inputs were in several cases statistically significant. However, the difference between limited and unlimited control authority was significant only in the low winds where limited authority required smaller inputs. Increased wind severity was a significant factor only for glide-slope error, control-wheel inputs, and control-column inputs.

In summary, throughout the three segments of the approach there were no instances in which limited control authority degraded any of the performance parameters. There were, however, instances where performance varied between subjects, and performance was generally degraded when wind severity increased.

Touchdown performance.- The mean touchdown-performance data are summarized in figure 17. The touchdown-performance parameters considered during this investigation were sink rate, indicated airspeed, and pitch attitude, the only parameters in reference 1 that showed any effect of either controls or subjects. The limits shown in figure 17 reflect Category II requirements discussed in reference 4. Although touchdown performance generally degraded as wind severity increased, the mean values of all three performance parameters were generally within these limits for all subjects and all wind conditions. In addition, there were no consistent differences due to subjects or levels of control authority. The only instance of consequence in which a statistically significant difference existed was when subject A landed at a higher indicated airspeed in severe winds than did subject C or D with unlimited control authority. None of the flights performed by subject D, either with full control authority or limited authority, resulted in loss of control in severe Kennedy-type wind shears. This performance capability in severe winds is comparable to that reported in reference 1 in which subjects A, B, and C never lost control when decoupled controls were used, but they crashed in 8 of 18 attempted landings in severe winds with the VCWS system.

CONCLUDING REMARKS

A fixed-base simulation study (NASA TP-1734) reported the beneficial effects of a decoupled longitudinal control system during the approach and landing of the NASA Terminal Configured Vehicle (TCV) Aft Flight Deck Simulator in the presence of severe wind shear. The decoupled control system employed the throttle, the elevators, and the symmetric spoilers as active control elements to provide steady-state decoupling of flight-path angle, pitch angle, and forward velocity. The present simulation study has been conducted to determine whether reduced spoiler and thrust authority would significantly degrade the approach and landing performance of the decoupled control system. The piloting task was to use the electronic attitude-direction indicator (EADI) to capture and maintain a 3^{o} glide slope and then use the perspective runway included on the display to complete the landing.

Increased wind severity again degraded the approach and landing performance. In addition, there were differences in performance between subjects, but the differences were generally restricted to the control-column and control-wheel activity during the approach. There were, however, no significant effects of reduced spoiler and thrust authority on performance either during the approach or during landing. Each approach resulted in a completed landing in all wind conditions.

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STATISTICAL ANALYSIS OF APPROACH- AND LANDING-PERFORMANCE PARAMETERS

This analysis has two objectives. It must determine whether the performance of subject D differed significantly from that of subjects A, B, and C of reference 1. It must also determine whether the performance of subject D with limited control authority (spoiler travel and thrust level) differed significantly from his performance with full authority. The data for limited control authority were treated as data from another subject (labeled subject D*) and along with the data of subject D with full authority was combined with the data of subjects A, B, and C of reference 1.

An analysis of variance (ANOV) (refs. 5 and 6) was then performed on each performance parameter to determine whether either of the experimental factors (subjects or wind shears) or their interactions were statistically significant at the 95-percent confidence (5-percent significance) level or greater. In this experiment there were five levels of subjects (A, B, C, D, and D*) and three levels of wind shear (light, moderate, and severe). The resulting experiment employed six replicates for each condition for a total of 90 flights or 89 degrees of freedom. When the ANOV indicated that a given factor was significant, further testing was performed to determine at which levels of that factor the means were significantly different. The student's t-test was used for level testing for winds, and the Duncan multiple-range (DMR) test was used to test the subjects' performance.

Initial Approach Segment

The ANOV (table V) for the initial segment, between altitudes of 457.2 m and 228.0 m, showed that at the 95-percent confidence level there was no statistically significant difference due to subjects for flight-path-angle error, glide-slope error, or indicated-airspeed error. Control-column activity showed a significant subject effect as did localizer error and control-wheel activity, two performance parameters associated with the lateral mode. Wind conditions were a statistically significant factor, at the 95-percent confidence level, for all six performance parameters. There were, however, no statistically significant interaction effects. The results of level testing for the initial approach segment are presented in table VI along with the mean and standard deviation. When the t-test was applied to winds, the light shear condition was the reference against which the other winds were tested. An example of the Duncan multiple-range (DMR) test, used for level testing subjects, may be seen in table VI by considering control-wheel activity in moderate wind shear. Subject B used control-wheel inputs that were significantly larger, at the 95-percent confidence level, than those used by the other four subjects. Furthermore, the difference between the other four subjects was not statistically significant. The six approach-performance parameters are discussed in detail in the following paragraphs.

Flight-path-angle error.- The flight-path-angle error was statistically unaffected by subjects and, hence, was also unaffected by control authority. The degradation in performance due to increased wind shear was statistically significant (table VI) for one subject out of five in moderate winds and for two subjects in severe winds.

Glide-slope error.- There was no statistically significant difference in glide-slope error due to subjects or control authority. Severe wind shear degraded glide-slope performance by an amount that was statistically significant for four of the five subjects.

Localizer error.- Localizer error showed a statistically significant effect (table V) of both subjects and winds. However, the effects were not widespread. Subject D made larger errors (table VI) than subjects A, B, and C, but only in light winds. The degradation due to winds was statistically significant in only 1 of the 10 cases: when moderate winds resulted in poorer performance for subject A.

Indicated-airspeed error.- There was no statistically significant difference in indicated-airspeed error due to subjects or control authority. The degradation due to wind shear was statistically significant for three of the five subjects in both moderate and severe wind shear.

Control-wheel activity.- Control-wheel inputs showed a statistically significant effect of subjects. However, the effect was the result of subject B using larger inputs than those used by subjects A, C, D, and D^* in moderate and severe winds. There was no significant difference due to control authority (because the performance of subject D was not significantly different from that of subject D^*). Larger control-wheel inputs were used as wind severity increased, but the difference in means was statistically significant for only one subject (subject B) in either wind case.

Control-column activity.- Control-column inputs showed a statistically significant effect of subjects and control authority. However, the differences were significant only in moderate winds. In a like manner, the wind effect was significant only for severe winds and then only for one subject.

Intermediate Approach Segment

The ANOV (table VII) for the intermediate segment, between altitudes of 76.2 m and 30.5 m, was almost identical to that for the initial approach segment. Subject and control-authority effects were not statistically significant at the 95-percent level for flight-path-angle error, glide-slope error, and indicated-airspeed error. Wind effects were again statistically significant, at the 95-percent level, for all six performance parameters. In addition, interaction effects between winds and subjects were statistically significant for control-column inputs.

Flight-path-angle error.- Subjects (and control authority) did not have a statistically significant effect (table VII) on flight-path angle. Winds were a statistically significant factor, but the difference in means was significant only for one subject (table VIII) in severe winds; whereas the degradation due to moderate winds was not significant for any of the subjects.

Glide-slope error.- Glide-slope error did not show a statistically significant effect (table VII) of subjects or control authority. In severe winds, however, subject D with limited control authority had a significantly smaller standard deviation than three of the four remaining subjects. Consequently, the statistical significance of the difference in means was probably suppressed in severe winds. Moderate winds did not statistically degrade glide-slope error (table VIII), but severe winds degraded performance for four of the five subjects.

Localizer error.- Localizer error showed a statistically significant effect of subjects (table VIII). There was no subject effect in light winds, but subject D made significantly larger errors than those made by the other four subjects in both moderate and severe winds. The difference in localizer error due to control authority, although statistically significant, is not believed to be particularly important because subject D made larger errors with unlimited control authority than he did with limited authority. The degradation due to wind shear was not widespread. Two of the five subjects showed a significant wind effect in moderate winds, and only one subject showed an effect in severe winds.

Indicated-airspeed error.- There was no statistically significant difference in indicated-airspeed error due to subjects or control authority. The degradation due to winds was statistically significant for three of the five subjects in moderate winds and for two of the five subjects in severe winds.

Control-wheel activity.- The statistically significant effect of subjects was the result of subject B using larger inputs than the other four subjects in light and moderate winds. In severe winds subject B and subject D^* (with limited control authority) used larger inputs than those used by the other three subjects, but the difference was statistically significant only when compared with the performance of subject C. There was no significant difference due to control authority. Increased wind severity generally resulted in larger control-wheel inputs, but the difference was statistically significant for only one subject.

Control-column activity.- Subject D used larger control inputs (table VIII) than those used by the other subjects in all wind conditions; however, the statistically significant differences are concentrated in severe wind shears. The difference due to control authority was also statistically significant in severe winds, but subject D actually made smaller inputs with limited authority than he did with full authority. Severe-wind-shear performance was significantly different from that in light winds for three of the five subjects.

Final Approach Segment

The ANOV (table IX) for the final segment, at altitudes between 30.5 m and 15.1 m, showed a statistically significant effect of subjects only for control-wheel and control-column inputs. Wind effects were statistically significant, at the 95-percent confidence level, for glide-slope error, indicated-airspeed error, control-wheel inputs, and control-column inputs. The only significant interaction effects occurred with the control-wheel inputs.

Flight-path-angle error.- Flight-path-angle error did not show a statistically significant effect (table IX), at the 95-percent confidence level, of subjects, control authority, or winds.

Glide-slope error.- Glide-slope error did not show a statistically significant effect (table IX) of subjects or control authority. The degradation in performance due to moderate winds was statistically significant (table X) for only one subject. However, severe winds resulted in a significant degradation for four of the five subjects.

Localizer error.- Localizer error did not show a statistically significant effect (table IX) of subjects, control authority, or winds.

Indicated-airspeed error.- Indicated-airspeed error did not show a statistically significant effect of subjects or control authority. The degradation in performance due to severe wind shear was statistically significant (table X) for three of the five subjects, whereas the degradation due to moderate winds was not statistically significant.

Control-wheel activity.- As was the case during the intermediate segment of the approach, the statistically significant effect of subjects was primarily the result of subject B using larger inputs than the other four subjects in light and moderate winds. In severe winds (table X) subject C and subject D* (with limited control authority) used significantly smaller control-wheel inputs than did subject D. Increased wind severity generally resulted in larger inputs, but the increase was statistically significant for only one subject in both moderate and severe winds.

Control-column activity.- Control-column activity showed a statistically significant effect of subjects (table IX), but the significant difference was generally limited to light winds (table X) where subject D used larger inputs than those used by the four other subjects. Wind effects were significant only when the performance in severe winds was compared with that in light winds, and then only for one of the five subjects.

Touchdown Performance

The ANOV (table XI) for the touchdown-performance parameter showed that subjects were a statistically significant factor, at the 95-percent confidence level, for only indicated airspeed. Winds were a statistically significant factor for indicated airspeed and pitch attitude. Subject and wind interaction effects were significant for indicated airspeed. The results of level testing are discussed in the following paragraphs.

Sink rate.- Sink rate at touchdown showed no significant effects of subjects, control authority, or wind severity.

Indicated airspeed.- The statistically significant effect of subjects on indicated airspeed occurred primarily in severe wind shear (table XII) where subject A landed at significantly higher speeds than subjects C, D, and D*. Although winds were a statistically significant factor (table XI), the effect was not widespread with severe winds resulting in significantly higher speeds (table XII) for only one of the five subjects.

Pitch attitude.- Subjects (and control authority) were not statistically significant for pitch attitude. Winds were statistically significant, but moderate winds resulted in pitch angles that were significantly different from the light-wind case for only one subject. In addition, pitch angles in severe winds differed significantly from those in light winds for two subjects.

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TABLE I.- PHYSICAL CHARACTERISTICS OF BOEING 737-100 AIRPLANE

General:	
Overall length, m	28.65
Height to top of vertical fin, m	11.28
Wing:	
Area, m^2	91.04
Span, m	28.35
Mean aerodynamic chord, m	3.41
Incidence angle, deg	1
Aspect ratio	8.83
Taper ratio	0.279
Dihedral, deg	6
Sweep (quarter-chord), deg	25
Flap deflection (maximum), deg	40
Aileron deflection (maximum), deg	±20
Spoilers deflection (maximum):	
Inboard ground spoilers (maximum), deg	60
All other spoilers (maximum), deg	40
Horizontal tail:	
Total area, m^2	28.99
Span, m	10.97
Stabilizer deflection (maximum), deg	-14, +3
Elevator deflection (maximum), deg	±21
Vertical tail:	
Total area, m^2	20.8
Rudder deflection, deg	±24
Weight:	
Maximum take-off gross weight, kN	431
Design landing weight, kN	399
Operational empty weight, kN	297
Propulsion system (two Pratt & Whitney JT8D-9 engines):	
Maximum uninstalled thrust per engine at sea-level static, kN	62.3
Effective engine moment arms about center of gravity:	
Lateral arm, m	4.94
Vertical arm, m	1.52

TABLE II.- INITIAL CONDITIONS FOR SIMULATION

Weight, kN	408
Moments of inertia:	
I_X, kg-m^2	602 000
I_Y, kg-m^2	1 090 000
I_Z, kg-m^2	1 780 000
I_{XZ}, kg-m^2	71 600
Center of gravity, percent of mean aerodynamic chord	30
Altitude, m	457
Field elevation, m	2
Indicated airspeed, knots	130
Flight-path angle, deg	0
Trailing-edge flap position, deg	40
Flight-spoiler initial position (decoupled controls), deg	9
Landing-gear position	Down

TABLE III.- TURBULENCE SPECIFICATIONS FOR LIGHT WIND SHEARS

(a) Wind-shear B2 profile

Altitude, m	rms longitudinal velocity, knots	rms lateral velocity, knots	rms vertical velocity, knots	Longitudinal scale length, m	Lateral scale length, m	Vertical scale length, m
6.10	0.65	0.65	0.09	32.22	15.15	3.17
22.86	1.63	1.63	.15	55.47	32.89	12.10
45.72	3.61	3.61	.25	79.74	53.00	24.23
91.44	4.76	4.76	.31	112.78	84.28	48.46
137.16	.50	.50	.09	139.57	111.59	72.69
182.88	.25	.25	.06	161.82	135.82	96.93
228.60	0	0	0	161.82	135.82	96.93
457.20	0	0	0	161.82	135.82	96.93

(b) Wind-shear B3 profile

Altitude, m	rms longitudinal velocity, knots	rms lateral velocity, knots	rms vertical velocity, knots	Longitudinal scale length, m	Lateral scale length, m	Vertical scale length, m
6.10	0.65	0.65	0.09	79.49	79.49	1.52
22.86	1.63	1.63	.15	674.85	674.85	5.72
45.72	3.61	3.61	.25	2383.31	2383.31	11.43
91.44	4.76	4.76	.31	5389.73	5389.73	22.86
137.16	.50	.50	.09	1058.33	1058.33	34.29
182.88	.25	.25	.06	793.75	793.75	45.72
228.60	0	0	0	793.75	793.75	45.72
457.20	0	0	0	793.75	793.75	45.72

TABLE IV.- TURBULENCE SPECIFICATIONS FOR WIND SHEAR B7, D3, AND D10 PROFILES

Altitude, m	rms longitudinal velocity, knots	rms lateral velocity, knots	rms vertical velocity, knots	Longitudinal scale length, m	Lateral scale length, m	Vertical scale length, m
6.10	3.40	2.70	2.34	32.23	15.15	3.17
30.49	4.05	3.46	3.53	66.07	40.91	16.16
60.98	4.43	3.95	4.35	93.45	65.09	32.32
121.95	4.85	4.50	5.36	132.16	103.54	64.63
182.93	5.11	4.86	6.05	161.86	135.85	96.95
457.32	5.74	5.78	7.94	256.37	251.37	242.47

TABLE V.- ANALYSIS OF VARIANCE FOR rms APPROACH PARAMETERS WITH SUBJECTS AND WIND AS EXPERIMENTAL FACTORS BETWEEN ALTITUDES OF 457.2 m AND 228.0 m

Experimental factors	$\Delta\gamma$		GSE		ELOC		ΔIAS		δ_{wh}		δ_{col}	
	d.o.f.	F	d.o.f.	F	d.o.f.	F	d.o.f.	F	d.o.f.	F	d.o.f.	F
Subject	4	0.31	4	0.16	4	[a]4.04	4	1.42	4	[a]11.23	4	[a]2.62
Wind	2	[a]15.25	2	[a]16.75	2	[a]7.04	2	[a]9.05	2	[a]7.98	2	[a]6.52
Interaction . . .	8	0.88	8	0.67	8	0.35	8	1.16	8	1.49	8	0.85
Error	75	-----	75	-----	75	----	75	----	75	-----	75	----

[a]Statistical significance at the 5-percent level (F_{cr} = 3.12, 2.49, and 2.06 for 2, 4, and 8 d.o.f., respectively).

TABLE VI.- rms APPROACH DATA BETWEEN ALTITUDES OF 457.2 m AND 228.0 m

Experimental factor	Statistical parameter	Light shears for subject -					Moderate shears for subject -					Severe shears for subject -				
		A	B	C	D	D*	A	B	C	D	D*	A	B	C	D	D*
$\Delta\gamma$, deg	Mean	0.20	0.20	0.12	0.06	0.16	0.19	0.30	0.33	0.06	0.34	0.60	0.47	0.56	0.90	0.87
	Standard dev.	0.20	0.10	0.07	0.33	0.11	0.14	0.14	0.28	0.30	0.60	0.24	0.31	0.50	1.06	0.30
	t (winds)	Ref.	Ref.	Ref.	Ref.	Ref.	0.17	0.54	1.40	1.70	**4.00	**2.89	0.89	2.04	1.87	**5.46
	DMR (subjects)	← Not statistically significant (ANOV) →														
GSE, m	Mean	18.05	9.95	14.94	15.21	13.99	19.73	19.16	21.05	15.05	22.31	28.89	34.08	33.59	34.53	24.84
	Standard dev.	11.77	1.73	8.00	9.11	4.06	8.86	14.19	16.90	5.14	13.63	11.00	12.36	15.37	17.50	8.10
	t (winds)	Ref.	Ref.	Ref.	Ref.	Ref.	0.28	1.50	0.80	0.03	1.43	1.65	**4.73	**2.64	**2.39	**2.92
	DMR (subjects)	← Not statistically significant (ANOV) →														
ELOC, m	Mean	16.35	15.21	21.81	72.80	40.74	56.34	43.00	38.54	96.74	98.54	18.78	15.43	14.68	41.90	37.00
	Standard dev.	13.41	14.43	23.78	93.21	45.42	39.86	43.78	24.79	76.23	70.39	15.38	7.22	15.03	41.98	39.03
	t (winds)	Ref.	Ref.	Ref.	Ref.	Ref.	**2.33	1.48	1.19	0.72	1.69	0.29	0.03	0.62	1.48	0.15
	DMR (subjects)	**(D-C), **(D-A), **(D-B)					Not statistically significant					Not statistically significant				
ΔIAS, knots	Mean	1.88	1.13	1.27	1.19	1.55	0.63	0.49	0.34	0.48	0.10	1.70	1.82	2.13	1.48	0.15
	Standard dev.	1.60	0.04	0.30	2.86	1.09	0.32	0.34	0.53	0.51	1.12	0.89	0.34	0.40	1.35	0.59
	t (winds)	Ref.	Ref.	Ref.	Ref.	Ref.	1.87	**4.57	**3.83	0.59	**2.27	0.24	**4.93	**4.30	0.22	**2.75
	DMR (subjects)	← Not statistically significant (ANOV) →														
δ_{wh}, deg	Mean	2.09	3.33	2.00	1.96	1.61	3.37	8.35	4.54	3.31	3.37	1.98	8.70	2.49	3.10	2.31
	Standard dev.	1.36	1.63	2.03	2.13	1.55	1.03	5.03	0.73	1.72	1.38	1.97	3.57	2.49	2.67	2.31
	t (winds)	Ref.	Ref.	Ref.	Ref.	Ref.	1.83	**2.32	1.38	1.21	2.07	0.11	**3.36	0.37	0.82	0.61
	DMR (subjects)	Not statistically significant					**(B-C), **(B-A), **(B-D*), **(B-D)					**(B-D), **(B-C), **(B-D*), **(B-A)				
δ_{col}, percent	Mean	7.00	4.00	3.67	2.50	2.90	8.00	3.33	0.00	0.70	9.67	13.67	8.33	3.00	13.23	10.17
	Standard dev.	8.00	3.33	7.33	4.23	2.40	6.00	5.33	0.00	1.10	11.37	9.00	14.00	6.33	7.30	7.80
	t (winds)	Ref.	Ref.	Ref.	Ref.	Ref.	0.25	0.25	1.22	1.10	1.41	1.33	0.76	0.17	**3.10	2.20
	DMR (subjects)	Not statistically significant					**(D*-D), **(A-C), **(D*-C)					Not statistically significant				

*Subject D with limited spoiler and thrust authority.
**Statistical significance at the 5-percent level.

TABLE VII.- ANALYSIS OF VARIANCE FOR rms APPROACH PARAMETERS WITH SUBJECTS AND WIND AS EXPERIMENTAL FACTORS BETWEEN ALTITUDES OF 76.2 m AND 30.5 m

Experimental factors	$\Delta\gamma$		GSE		ELOC		ΔIAS		δ_{wh}		δ_{col}	
	d.o.f.	F	d.o.f.	F	d.o.f.	F	d.o.f.	F	d.o.f.	F	d.o.f.	F
Subject	4	0.81	4	0.66	4	[a]3.78	4	0.42	4	[a]13.80	4	[a]12.90
Wind	2	[a]3.44	2	[a]22.87	2	[a]4.09	2	[a]8.79	2	[a]7.04	2	[a]17.79
Interaction . . .	8	1.03	8	1.15	8	1.62	8	0.52	8	1.08	8	[a]2.91
Error	75	----	75	-----	75	----	75	----	75	-----	75	-----

[a]Statistical significance at the 5-percent level (F_{cr} = 3.12, 2.49, and 2.06 for 2, 4, and 8 d.o.f., respectively).

TABLE VIII.- rms APPROACH DATA BETWEEN ALTITUDES OF 76.2 m AND 30.5 m

Experimental factor	Statistical parameter	Light shears for subject -					Moderate shears for subject -					Severe shears for subject -				
		A	B	C	D	D*	A	B	C	D	D*	A	B	C	D	D*
$\Delta\gamma$, deg	Mean	0.20	0.14	0.27	0.30	0.08	0.40	0.53	0.22	0.33	0.07	0.41	0.72	1.09	0.12	0.61
	Standard dev. . . .	0.12	0.09	0.21	0.49	0.18	0.53	0.55	0.22	0.47	0.25	0.29	0.52	0.94	0.80	1.51
	t (winds)	Ref.	Ref.	Ref.	Ref.	Ref.	0.91	1.70	0.42	0.11	0.91	1.62	**2.76	2.10	0.46	0.87
	DMR (subjects) . . .	← Not statistically significant (ANOV) →														
GSE, m	Mean	5.55	1.98	2.40	5.12	3.72	4.37	5.12	4.31	3.83	6.87	16.16	18.45	15.49	21.12	7.86
	Standard dev. . . .	3.50	0.91	2.19	3.01	1.55	2.27	3.92	3.95	2.12	5.58	15.20	17.27	9.64	11.80	3.13
	t (winds)	Ref.	Ref.	Ref.	Ref.	Ref.	0.69	1.91	1.04	1.29	1.33	1.67	**2.33	**3.24	**4.27	**2.90
	DMR (subjects) . . .	← Not statistically significant (ANOV) →														
ELOC, m	Mean	8.63	5.74	2.25	6.32	9.94	6.21	6.00	8.11	16.92	8.34	12.72	6.15	9.36	36.80	12.12
	Standard dev. . . .	6.72	2.63	2.33	7.01	9.09	3.64	3.28	6.02	8.57	4.04	8.81	3.45	6.36	42.00	7.48
	t (winds)	Ref.	Ref.	Ref.	Ref.	Ref.	0.78	0.09	**2.23	**2.35	0.39	0.90	0.23	**2.58	2.21	0.46
	DMR (subjects) . . .	Not statistically significant					**(D-D*), **(D-C), **(D-A), **(D-B)					**(D-A), **(D-D*), **(D-C), **(D-B)				
ΔIAS, knots	Mean	1.01	0.76	1.16	0.36	1.10	0.57	0.30	0.29	1.21	0.23	5.86	7.42	6.01	1.86	3.68
	Standard dev. . . .	0.55	0.31	0.43	2.93	0.72	0.52	0.82	0.37	3.27	0.64	2.79	4.59	4.75	3.27	5.38
	t (winds)	Ref.	Ref.	Ref.	Ref.	Ref.	1.77	**2.68	**4.20	**2.35	0.39	**4.52	2.06	**2.39	1.75	0.53
	DMR (subjects) . . .	← Not statistically significant (ANOV) →														
δ_{wh}, deg	Mean	1.74	7.15	0.59	3.03	1.73	3.40	11.07	1.50	4.97	3.85	5.90	8.10	2.76	8.30	3.82
	Standard dev. . . .	2.32	0.92	0.96	3.40	1.97	2.74	6.35	1.59	1.60	1.97	4.32	2.31	3.71	3.89	3.77
	t (winds)	Ref.	Ref.	Ref.	Ref.	Ref.	1.14	1.50	1.20	1.27	1.86	2.08	0.94	1.39	**2.50	1.20
	DMR (subjects) . . .	**(B-D), **(B-A), **(B-D*), **(B-C)					**(B-D), **(B-D*), **(B-A), **(B-C)					**(B-C), **(D*-C)				
δ_{col}, percent	Mean	6.00	3.67	0.00	13.10	7.13	3.00	8.33	0.00	11.83	13.77	5.33	19.33	5.33	42.93	26.30
	Standard dev. . . .	8.00	3.67	0.00	7.97	8.40	3.00	10.33	0.00	10.57	12.50	4.33	16.33	8.67	21.57	9.33
	t (winds)	Ref.	Ref.	Ref.	Ref.	Ref.	0.77	1.11	0.00	0.07	1.06	0.15	**2.38	1.44	**3.21	**3.80
	DMR (subjects) . . .	**(D-B), **(D-C)					**(D-C), **(D*-C)					**(D-D*), **(D-B), **(D*-A), **(D-A), **(D*-C), **(D-C)				

*Subject D with limited spoiler and thrust authority.
**Statistical significance at the 5-percent level.

TABLE IX.- ANALYSIS OF VARIANCE FOR rms APPROACH PARAMETERS WITH SUBJECTS AND WIND AS EXPERIMENTAL FACTORS BETWEEN ALTITUDES OF 30.5 m AND 15.1 m

Experimental factors	$\Delta\gamma$		GSE		ELOC		ΔIAS		δ_{wh}		δ_{col}	
	d.o.f.	F	d.o.f.	F	d.o.f.	F	d.o.f.	F	d.o.f.	F	d.o.f.	F
Subject	4	1.08	4	0.90	4	2.03	4	0.89	4	[a]5.41	4	[a]10.70
Wind	2	0.38	2	[a]24.93	2	0.61	2	[a]9.14	2	[a]13.26	2	[a]4.40
Interaction . . .	8	0.57	8	0.71	8	1.25	8	0.92	8	[a]2.26	8	0.90
Error	75	----	75	-----	75	----	75	----	75	-----	75	-----

[a]Statistical significance at the 5-percent level (F_{cr} = 3.12, 2.49, and 2.06 for 2, 4, and 8 d.o.f., respectively).

TABLE X.- rms APPROACH DATA BETWEEN ALTITUDES OF 30.5 m AND 15.1 m

Experimental factor	Statistical parameter	Light shears for subject -					Moderate shears for subject -					Severe shears for subject -				
		A	B	C	D	D*	A	B	C	D	D*	A	B	C	D	D*
$\Delta\gamma$, deg	Mean	0.42	0.28	0.49	0.68	0.20	0.66	0.66	0.81	0.63	0.18	0.79	0.84	0.66	0.11	0.19
	Standard dev.	0.29	0.29	0.30	0.62	0.31	0.69	0.59	0.86	1.28	0.39	0.68	0.58	0.81	1.53	1.06
	t (winds)	← Not statistically significant (ANOV) →														
	DMR (subjects)	← Not statistically significant (ANOV) →														
GSE, m	Mean	3.43	1.46	2.55	2.75	2.92	6.75	6.25	2.88	3.41	4.30	10.50	13.18	8.02	12.91	9.43
	Standard dev.	2.40	0.80	2.12	2.41	1.97	2.83	4.89	1.54	3.01	4.57	5.65	12.31	1.18	5.55	5.09
	t (winds)	Ref.	Ref.	Ref.	Ref.	Ref.	2.20	**2.37	0.31	0.42	0.67	**2.82	1.99	**5.53	**4.11	**2.95
	DMR (subjects)	← Not statistically significant (ANOV) →														
ELOC, m	Mean	7.51	4.22	2.66	7.04	7.58	3.31	4.35	9.02	9.84	7.19	9.48	2.77	8.10	8.20	7.66
	Standard dev.	4.55	2.68	2.98	7.29	4.54	2.04	2.53	6.20	5.96	3.59	7.57	1.09	3.78	8.01	7.06
	t (winds)	← Not statistically significant (ANOV) →														
	DMR (subjects)	← Not statistically significant (ANOV) →														
ΔIAS, knots	Mean	0.91	0.61	0.88	1.38	0.42	2.89	1.69	1.71	1.16	0.10	5.70	6.76	5.40	2.02	1.73
	Standard dev.	0.31	0.33	0.63	1.70	1.36	3.24	1.84	1.16	4.19	1.40	4.82	5.49	4.60	2.09	6.83
	t (winds)	Ref.	Ref.	Ref.	Ref.	Ref.	1.49	1.42	1.54	0.12	0.40	**2.43	**2.73	**2.39	0.58	0.42
	DMR (subjects)	← Not statistically significant (ANOV) →														
δ_{wh}, deg	Mean	1.35	6.97	0.69	3.51	1.80	1.67	12.21	1.98	5.94	2.53	5.51	6.58	1.76	10.80	4.26
	Standard dev.	1.14	2.28	1.05	4.59	2.05	2.01	6.31	1.03	3.61	2.37	4.52	5.27	2.08	3.60	4.93
	t (winds)	Ref.	Ref.	Ref.	Ref.	Ref.	0.34	**4.23	2.15	1.02	1.41	2.19	0.17	1.13	**3.05	1.13
	DMR (subjects)	**(B-D), **(B-D*), **(B-A), **(B-C)					**(B-D), **(B-D*), **(B-C), **(B-A)					**(D-D*), **(D-C)				
δ_{col}, percent	Mean	4.33	4.00	1.00	18.67	9.43	11.00	11.00	0.33	11.67	16.10	9.33	24.67	14.33	34.40	37.40
	Standard dev.	4.00	4.00	2.67	14.10	6.13	14.33	13.00	0.67	10.13	17.13	9.67	24.00	26.67	17.23	23.33
	t (winds)	Ref.	Ref.	Ref.	Ref.	Ref.	1.11	1.24	0.40	1.00	0.91	1.15	2.07	1.21	1.74	**2.80
	DMR (subjects)	**(D-D*), **(D-A), **(D-B), **(D-C)					Not statistically significant					**(D*-A) only significant pair				

*Subject D with limited spoiler and thrust authority.
**Statistical significance at the 5-percent level.

TABLE XI.- ANALYSIS OF VARIANCE FOR TOUCHDOWN PARAMETERS WITH SUBJECTS AND WINDS AS EXPERIMENTAL FACTORS

Experimental factors	$\dot{h}$		IAS		θ	
	d.o.f.	F	d.o.f.	F	d.o.f.	F
Subject	4	1.03	4	[a]2.65	4	1.36
Wind	2	2.23	2	[a]21.00	2	[a]4.43
Interaction . . .	8	0.77	8	[a]3.59	8	1.71
Error	75	----	75	-----	75	----

[a]Statistical significance at the 5-percent level (F_{cr} = 3.12, 2.49, and 2.06 for 2, 4, and 8 d.o.f., respectively).

TABLE XII.- TOUCHDOWN DATA

Experimental factor	Statistical parameter	Light shears for subject -					Moderate shears for subject -					Severe shears for subject -				
		A	B	C	D	D*	A	B	C	D	D*	A	B	C	D	D*
$\dot{h}$, m/sec	Mean	-1.13	-1.13	-0.76	-1.23	-0.93	-1.35	-0.92	-1.14	-0.95	-1.47	-1.65	-1.08	-1.35	-1.21	-1.34
	Standard dev. . . .	0.43	0.52	0.47	0.57	0.41	0.89	0.88	0.52	0.30	0.31	0.34	0.40	0.97	0.45	0.46
	t (winds)	← Not statistically significant (ANOV) →														
	DMR (subjects) . . .	← Not statistically significant (ANOV) →														
IAS, knots	Mean	124.65	124.56	124.28	123.50	125.17	124.42	121.73	124.17	126.33	124.50	134.86	130.10	127.56	127.33	124.83
	Standard dev. . . .	1.27	1.58	1.11	3.27	0.41	2.24	4.48	1.35	2.42	1.22	2.77	6.98	3.87	5.01	2.14
	t (winds)	Ref.	Ref.	Ref.	Ref.	Ref.	0.22	1.46	0.15	1.70	1.26	**8.23	1.90	2.00	1.58	0.38
	DMR (subjects) . . .	Not statistically significant					**(D*-B) only significant pair					**(A-C), **(A-D), **(A-D*)				
θ, deg	Mean	2.37	2.63	2.32	2.37	2.58	2.13	2.30	2.06	2.63	2.48	2.32	1.97	2.17	2.37	2.00
	Standard dev. . . .	0.26	0.11	0.20	0.67	0.10	0.36	0.37	0.18	0.33	0.37	0.27	0.48	0.39	0.51	0.54
	t (winds)	Ref.	Ref.	Ref.	Ref.	Ref.	1.33	2.06	**2.36	0.87	0.67	0.33	**3.30	0.83	0.00	**2.64
	DMR (subjects) . . .	← Not statistically significant (ANOV) →														

*Subject D with limited spoiler and thrust authority.
**Statistical significance at the 5-percent level.

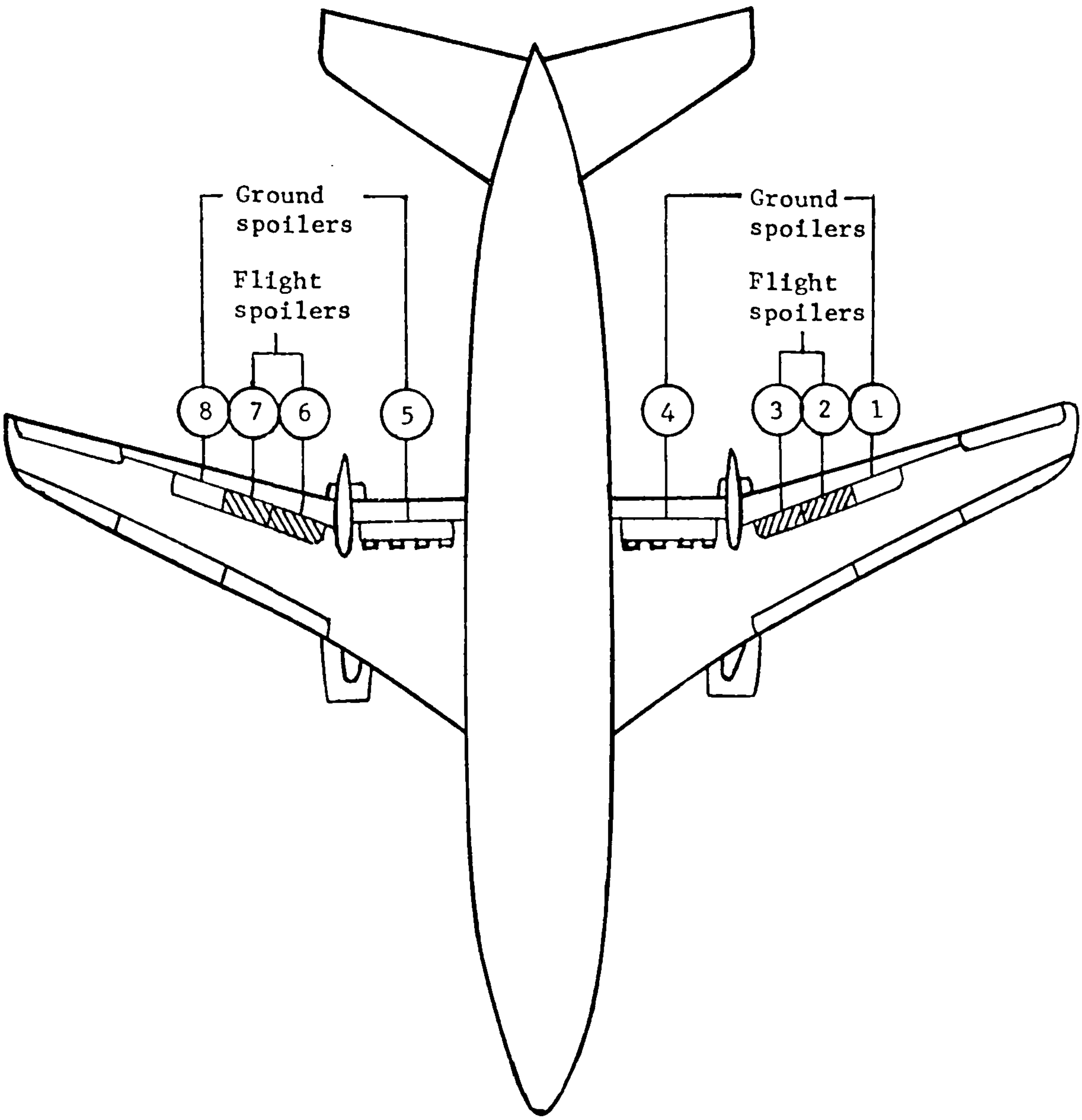

Figure 1.- Spoiler arrangement on the TCV airplane.

L-79-640.1

Figure 2.- AFD cockpit control and display layout.

(1) Roll pointer
(2) Roll scale
(3) Pitch grid
(4) Radar altitude
(5) Airplane reference symbol
(6) Speed error indicator
(7) Glide-slope error indicator
(8) Localizer error indicator
(9) Runway symbol
(10) Track pointer
(11) Pitch reference line
(12) Flight-path acceleration
(13) Flight-path angle
(14) Commanded flight-path angle

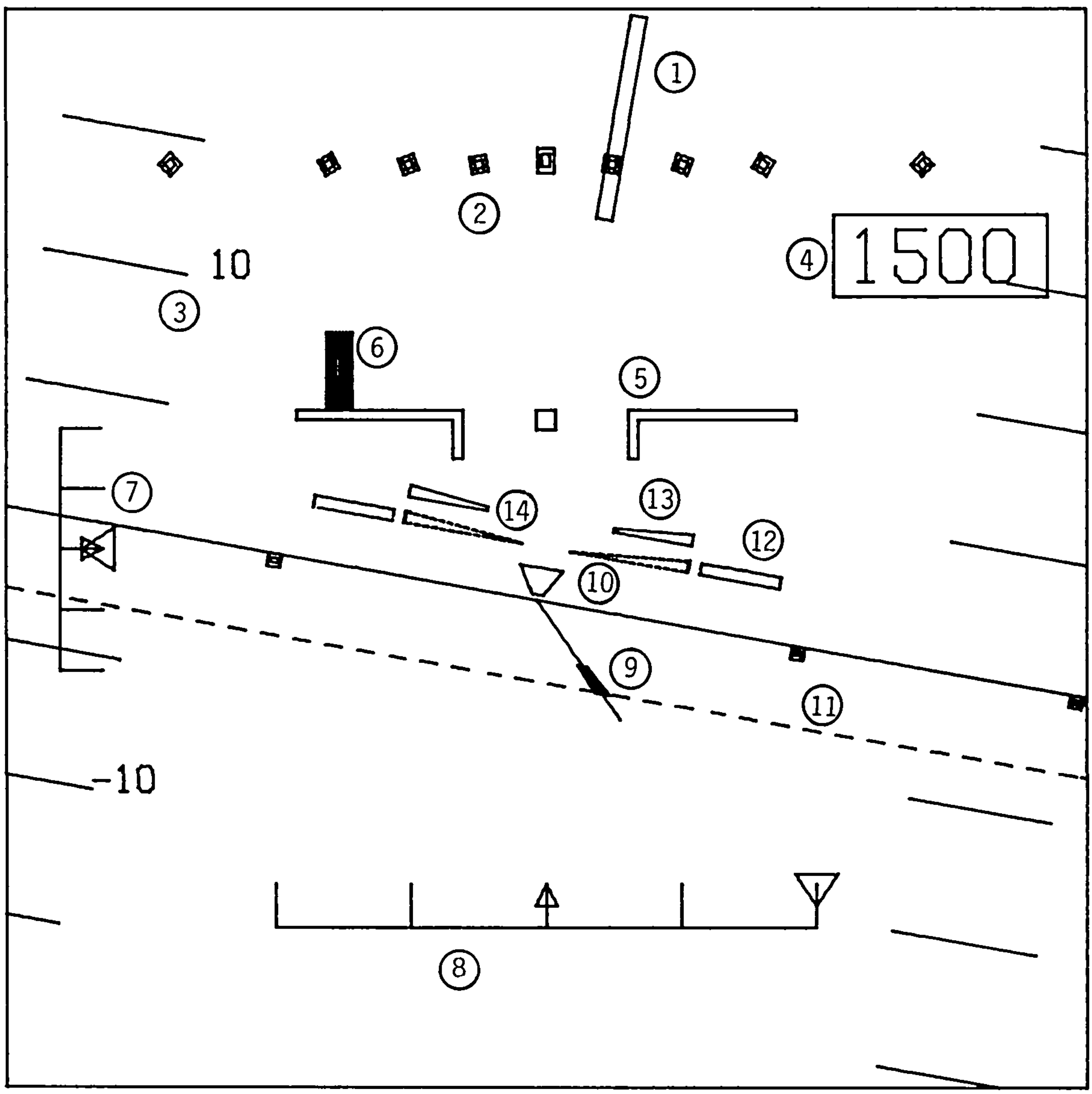

Figure 3.- Sketch of EADI.

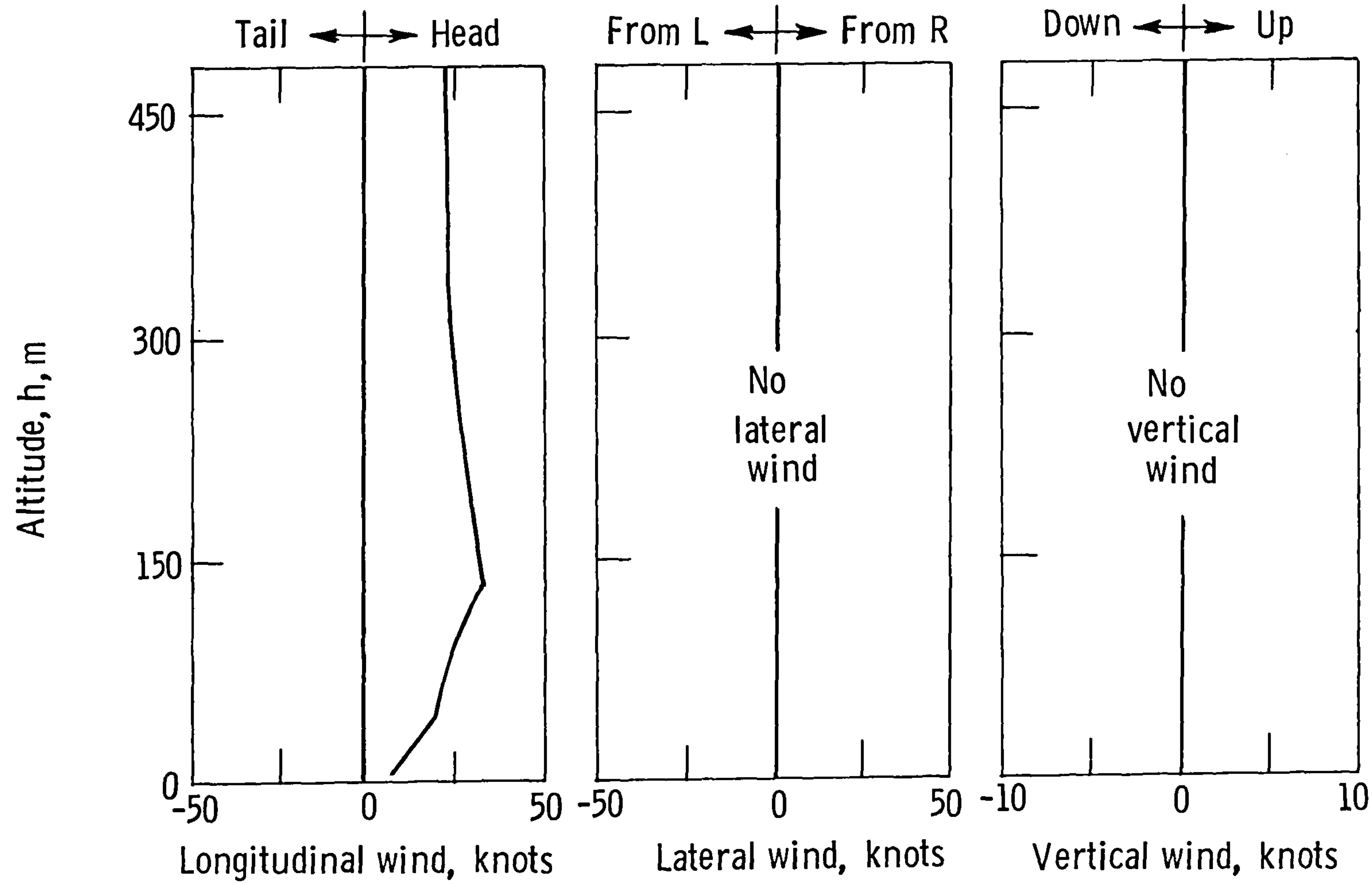

Figure 4.- Wind-shear B2 profile (low severity).

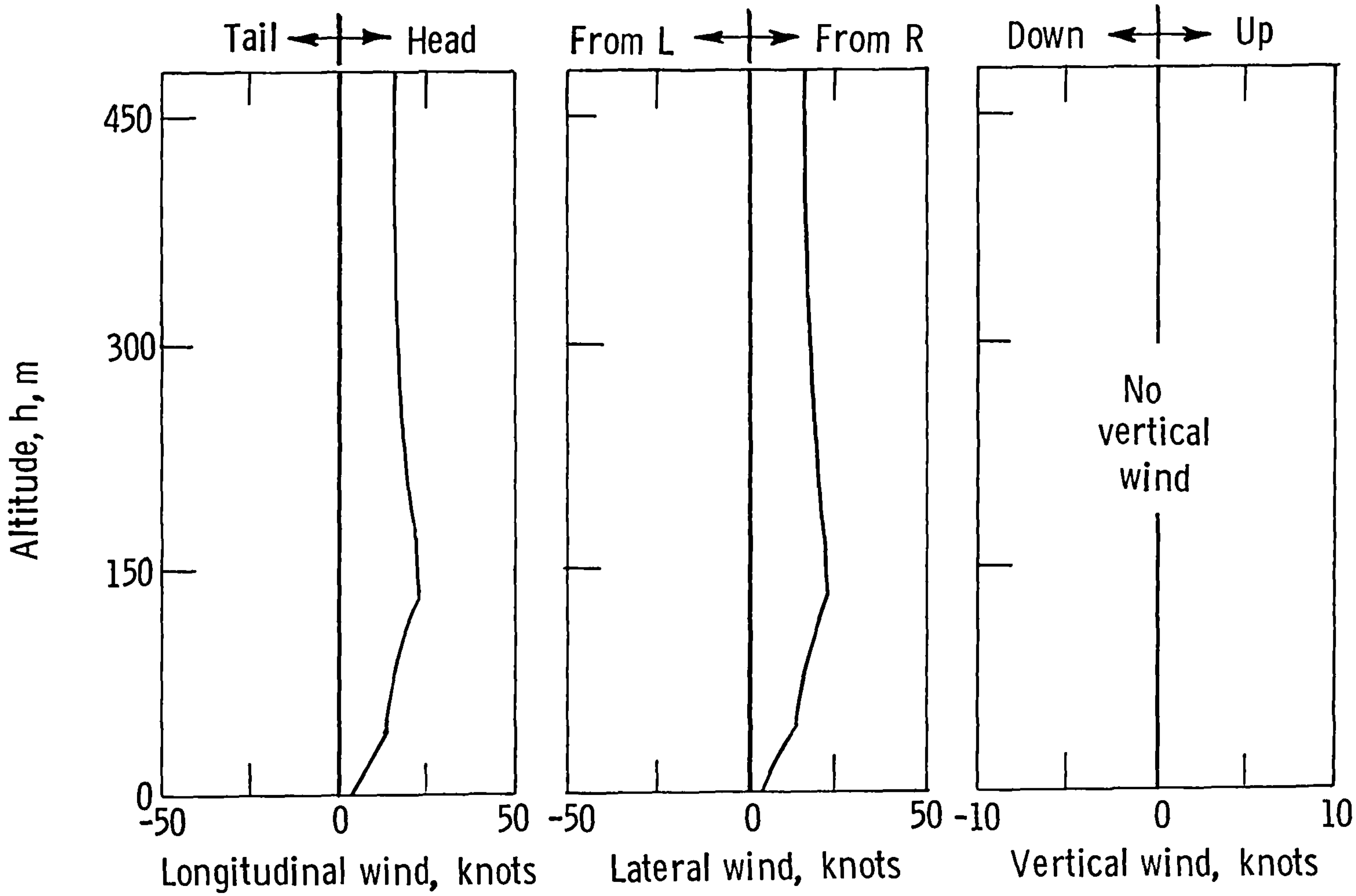

Figure 5.- Wind-shear B3 profile (low severity).

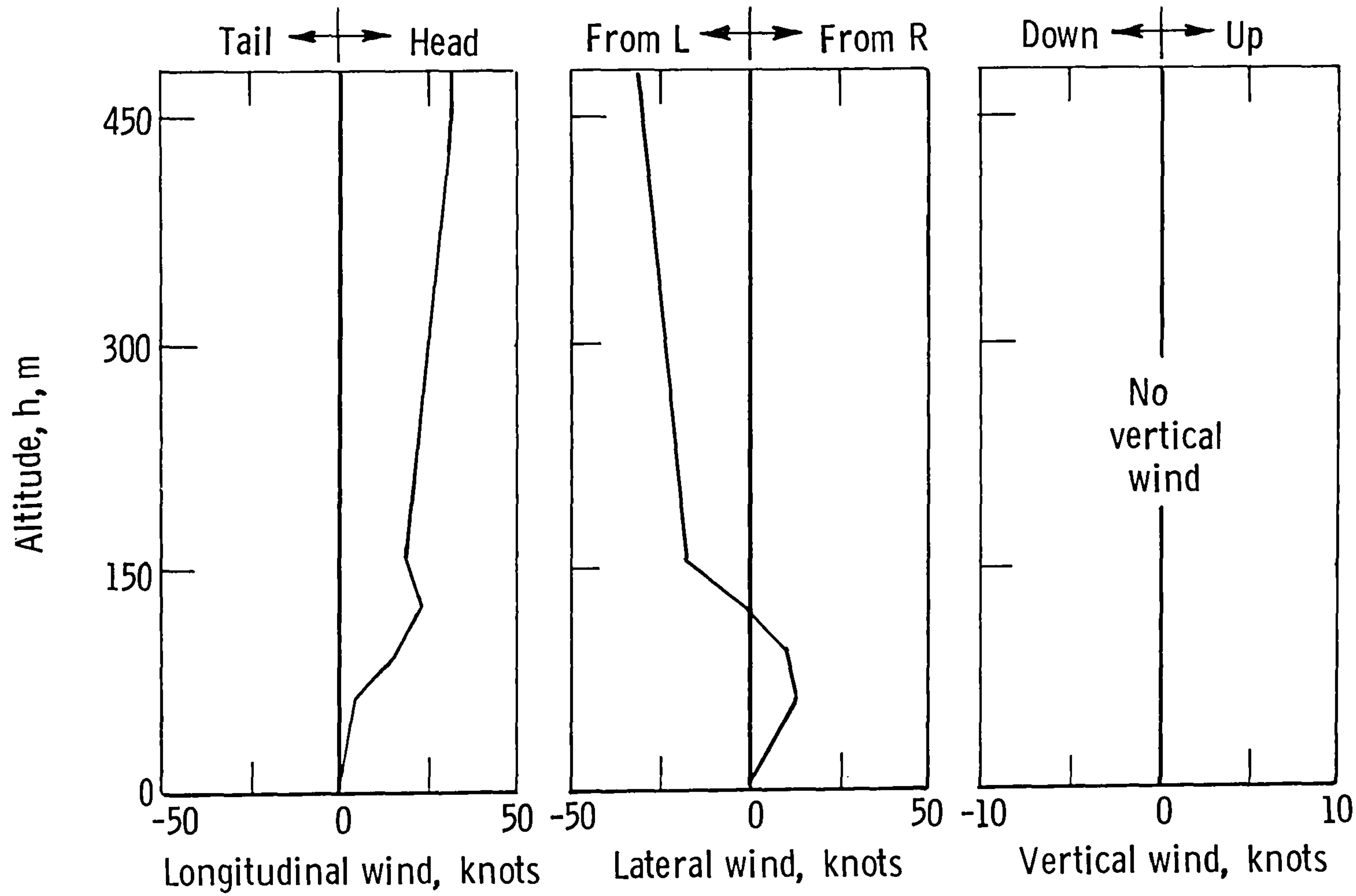

Figure 6.- Wind-shear B6 profile (moderate severity).

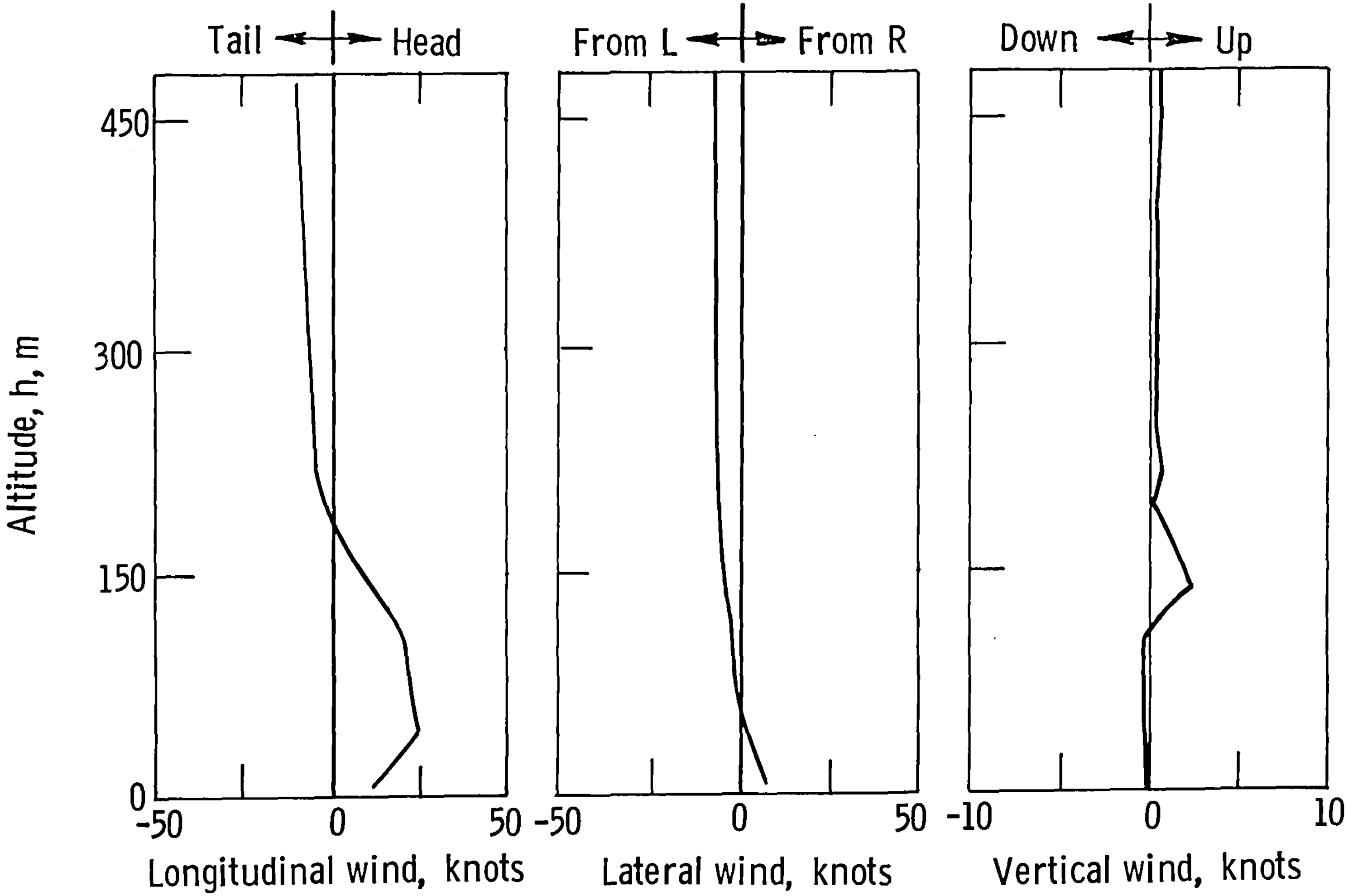

Figure 7.- Wind-shear B7 profile (moderate severity).

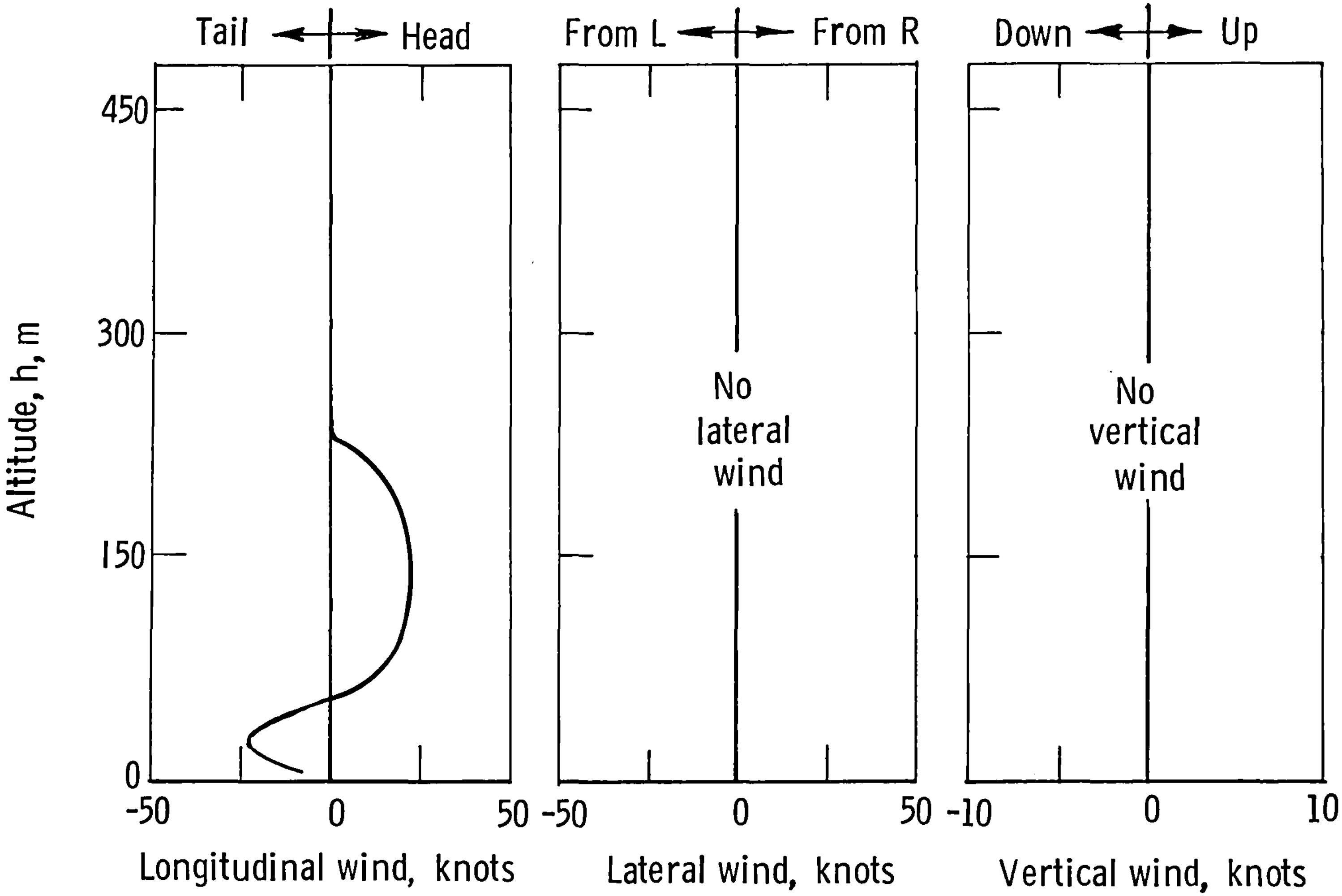

Figure 8.- Wind-shear D3 profile (high severity).

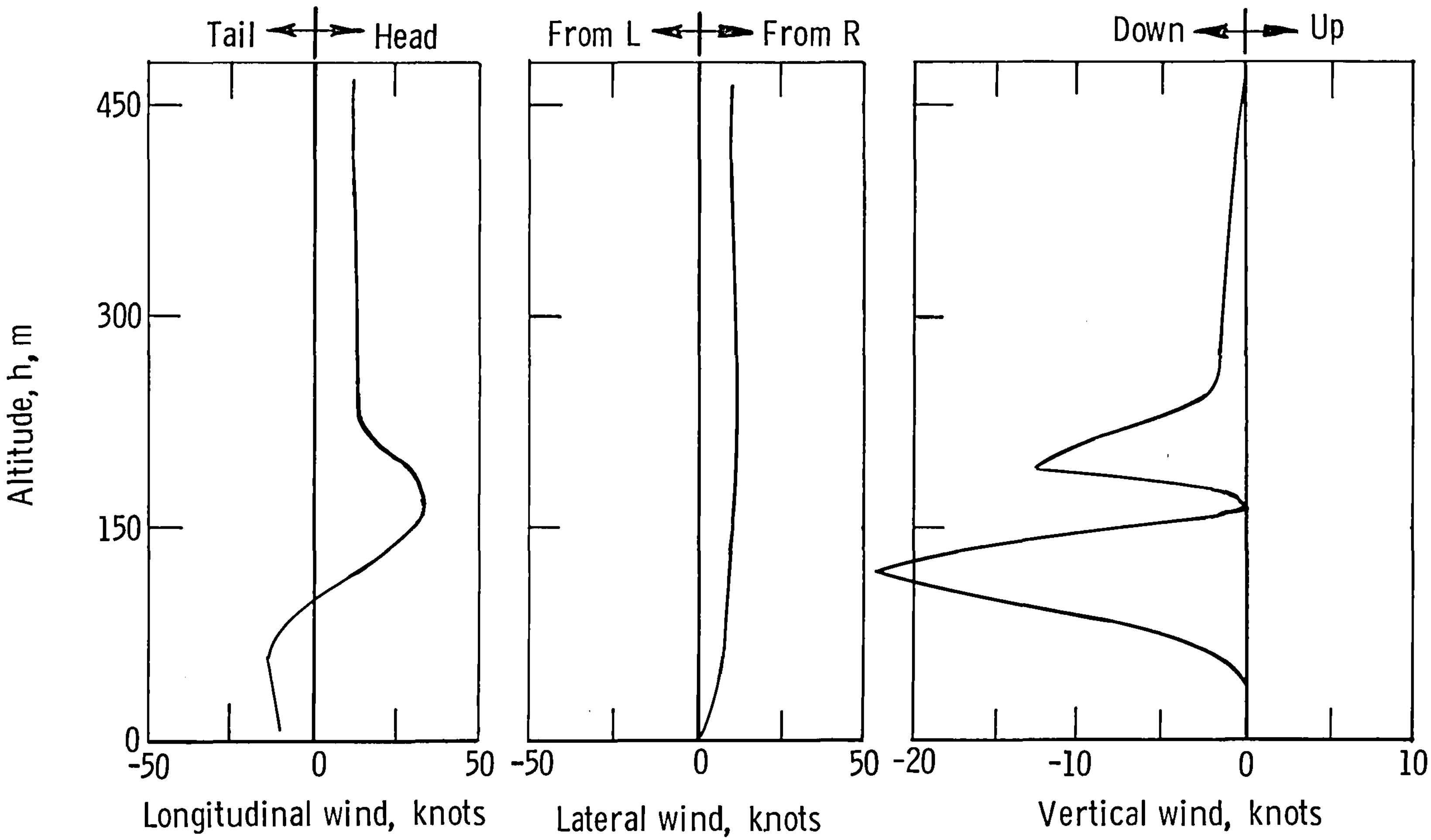

Figure 9.- Wind-shear D10 profile (high severity). Similar to profile at 1975 Eastern Airlines crash at John F. Kennedy International Airport.

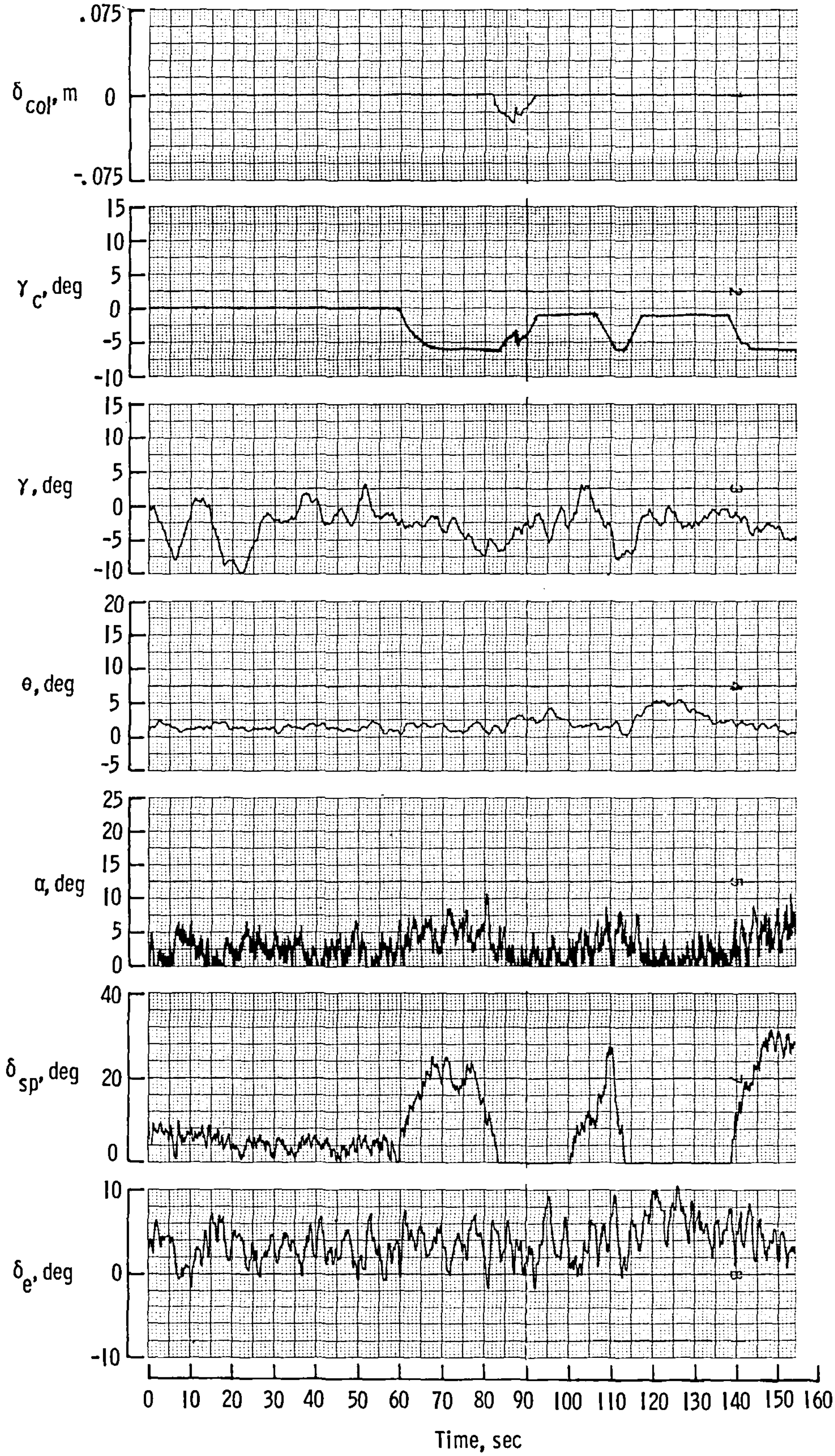

Figure 10.- Typical flight performed in Kennedy-type D10 wind shear.

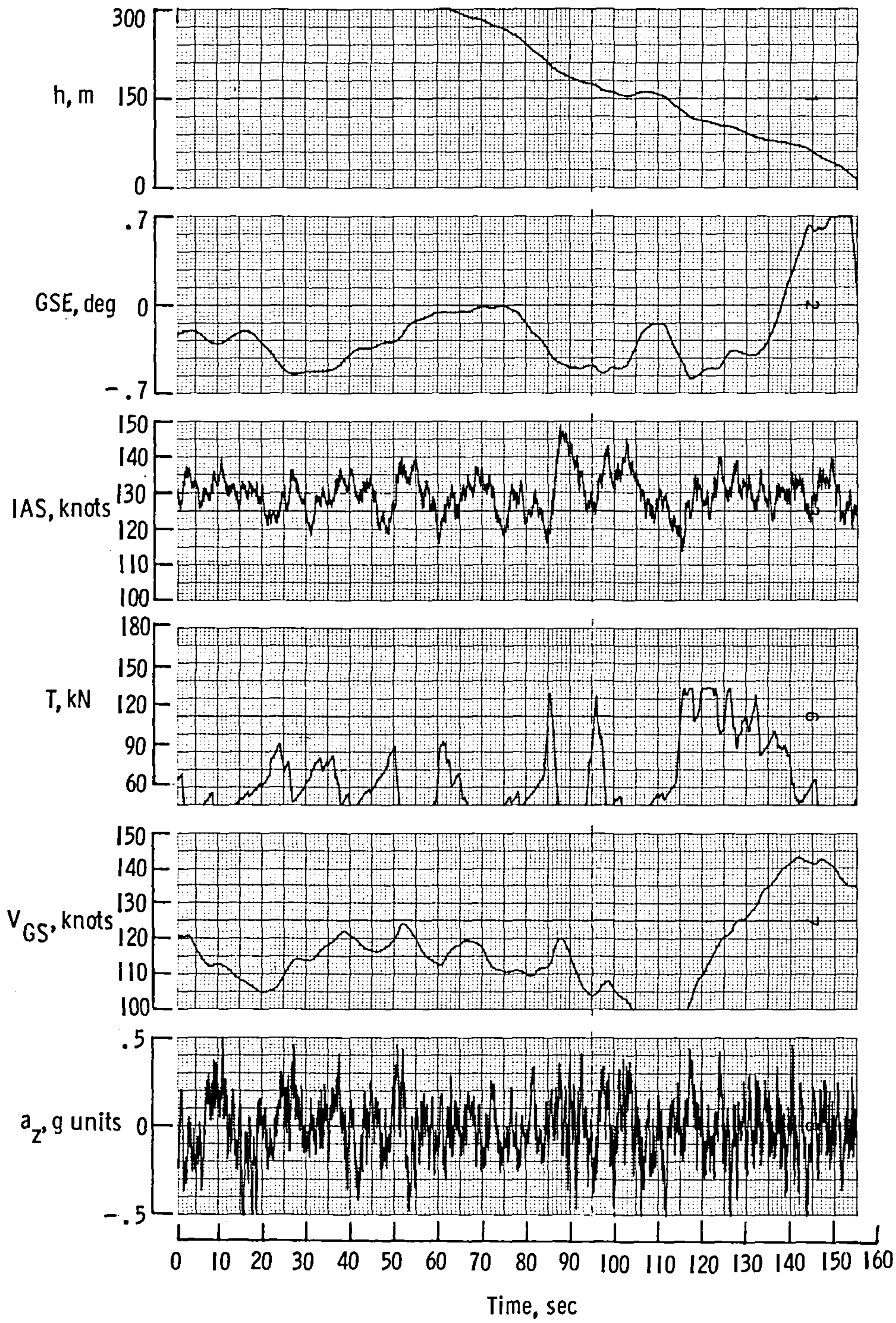

Figure 10.- Concluded.

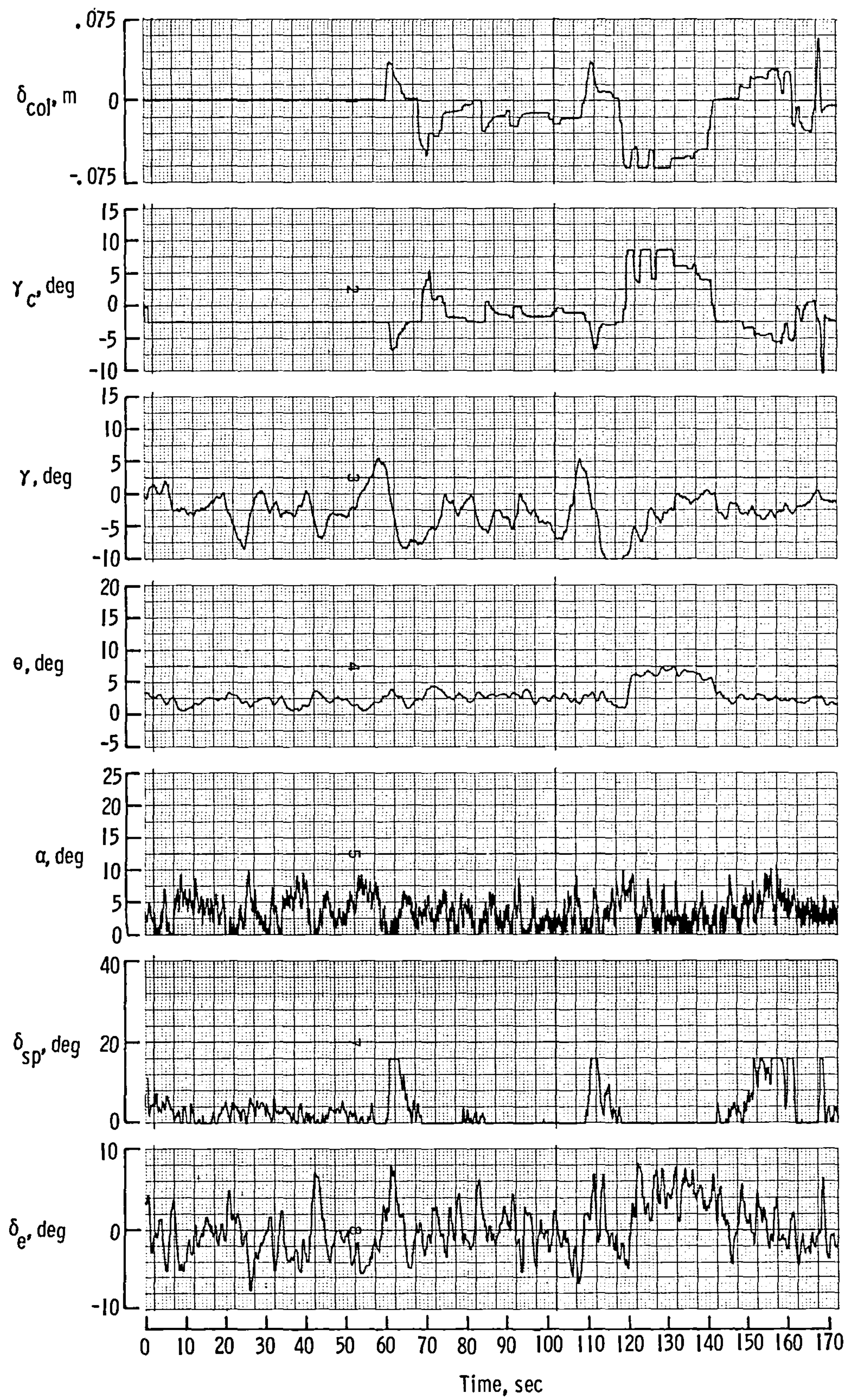

Figure 11.- Typical flight performed in Kennedy-type D10 wind shear with limited control authority.

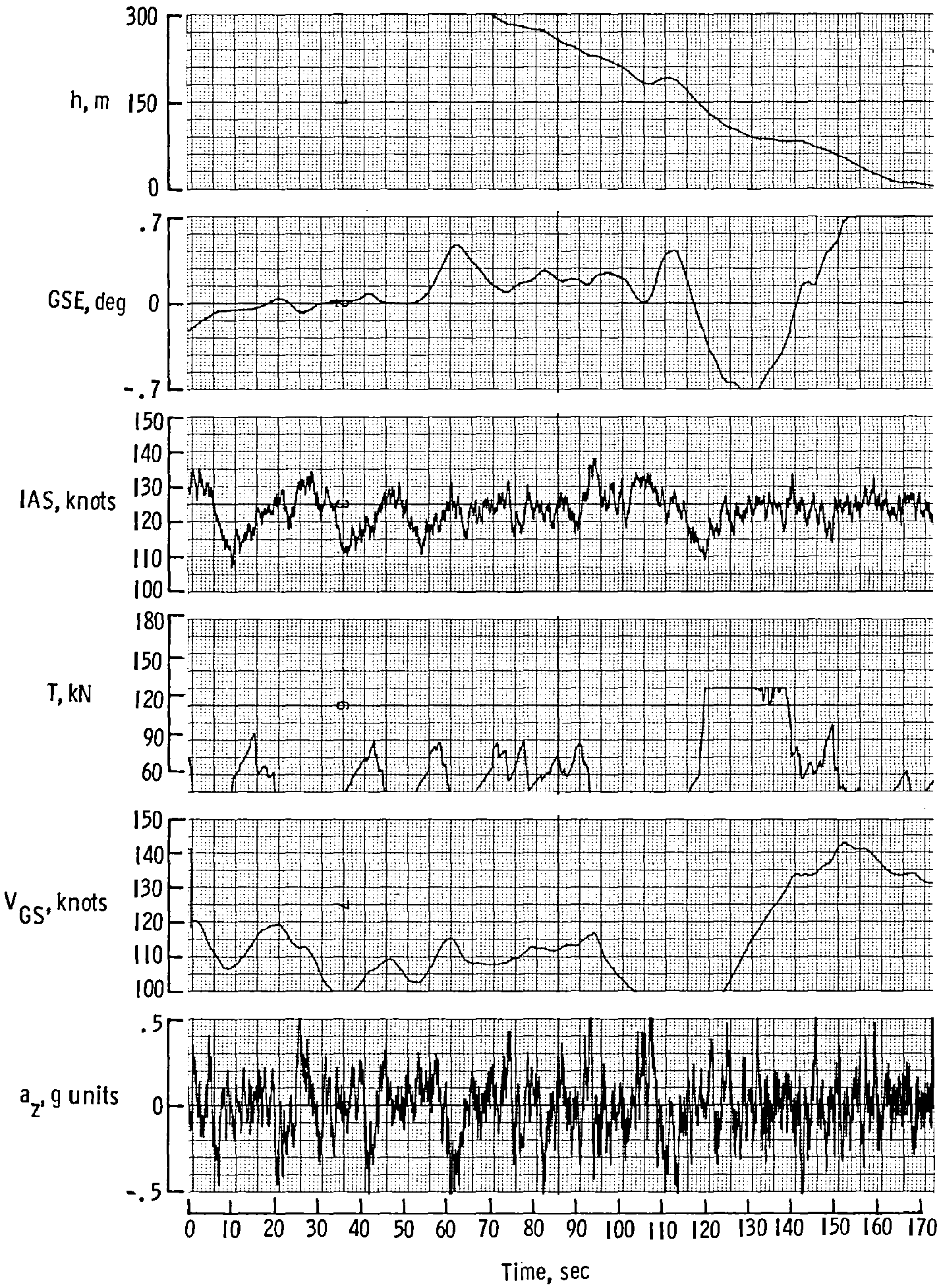

Figure 11.- Concluded.

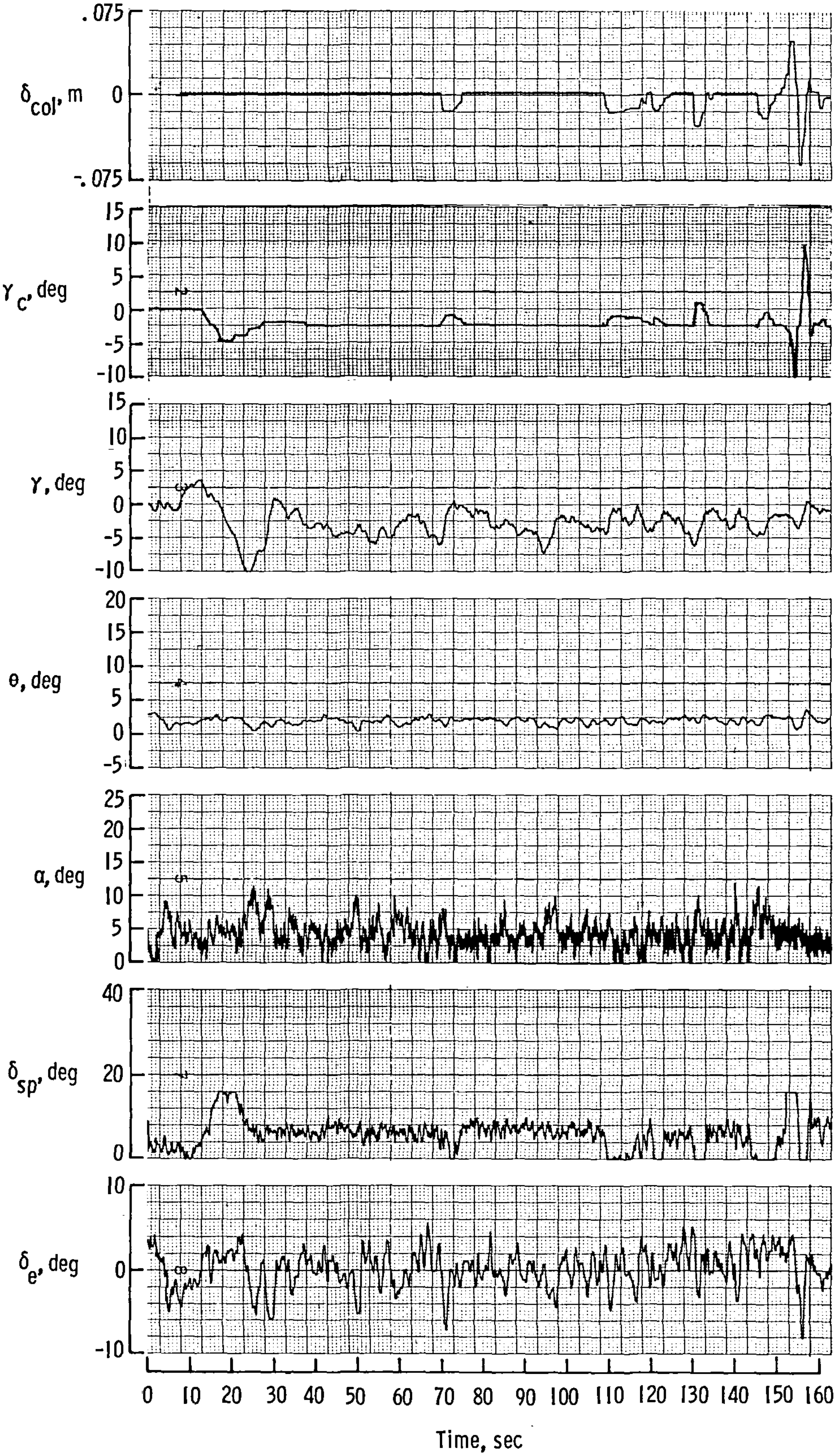

Figure 12.- Typical flight performed in severe D3 wind shear (similar to Kennedy type but without vertical wind component) with limited control authority.

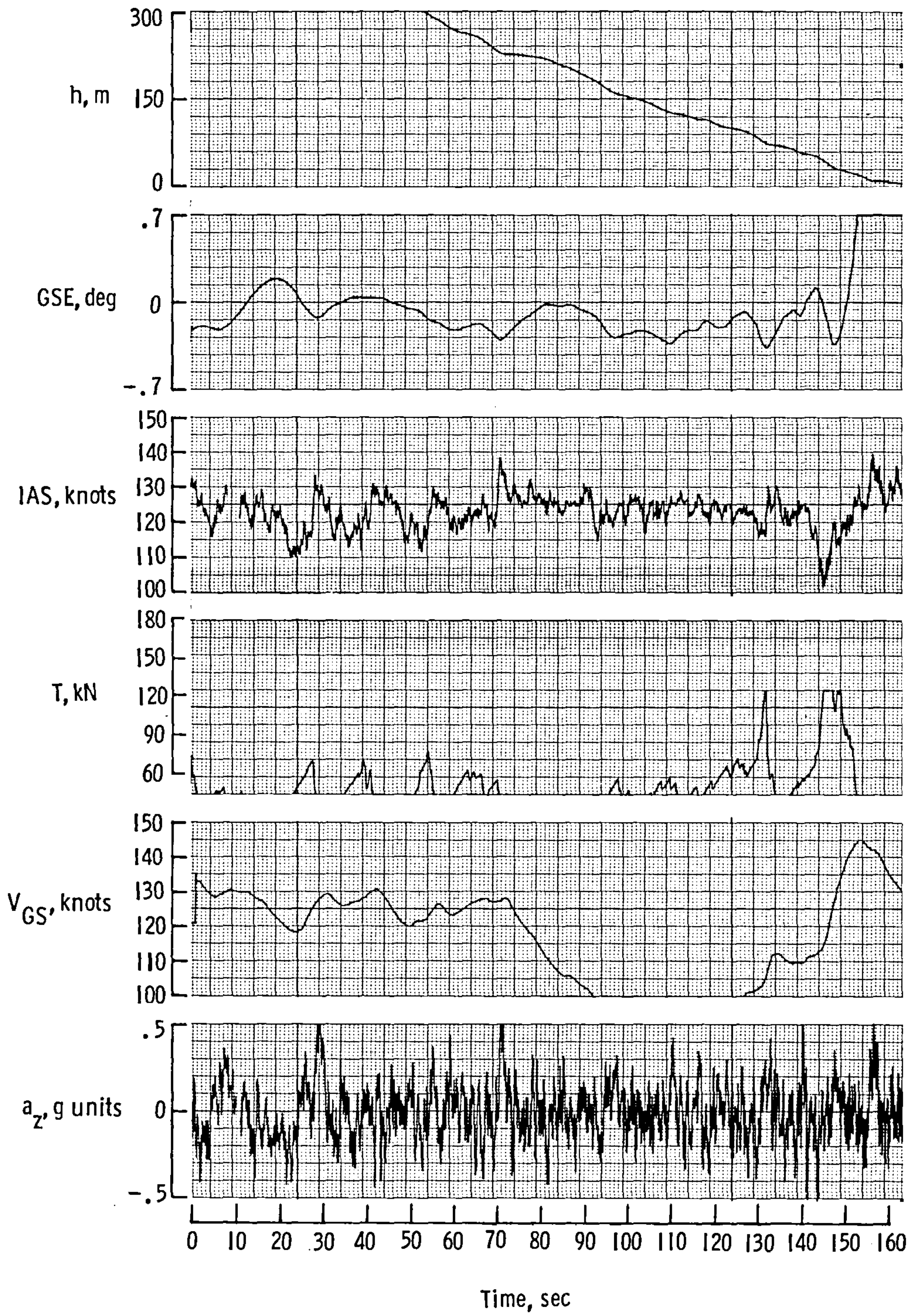

Figure 12.- Concluded.

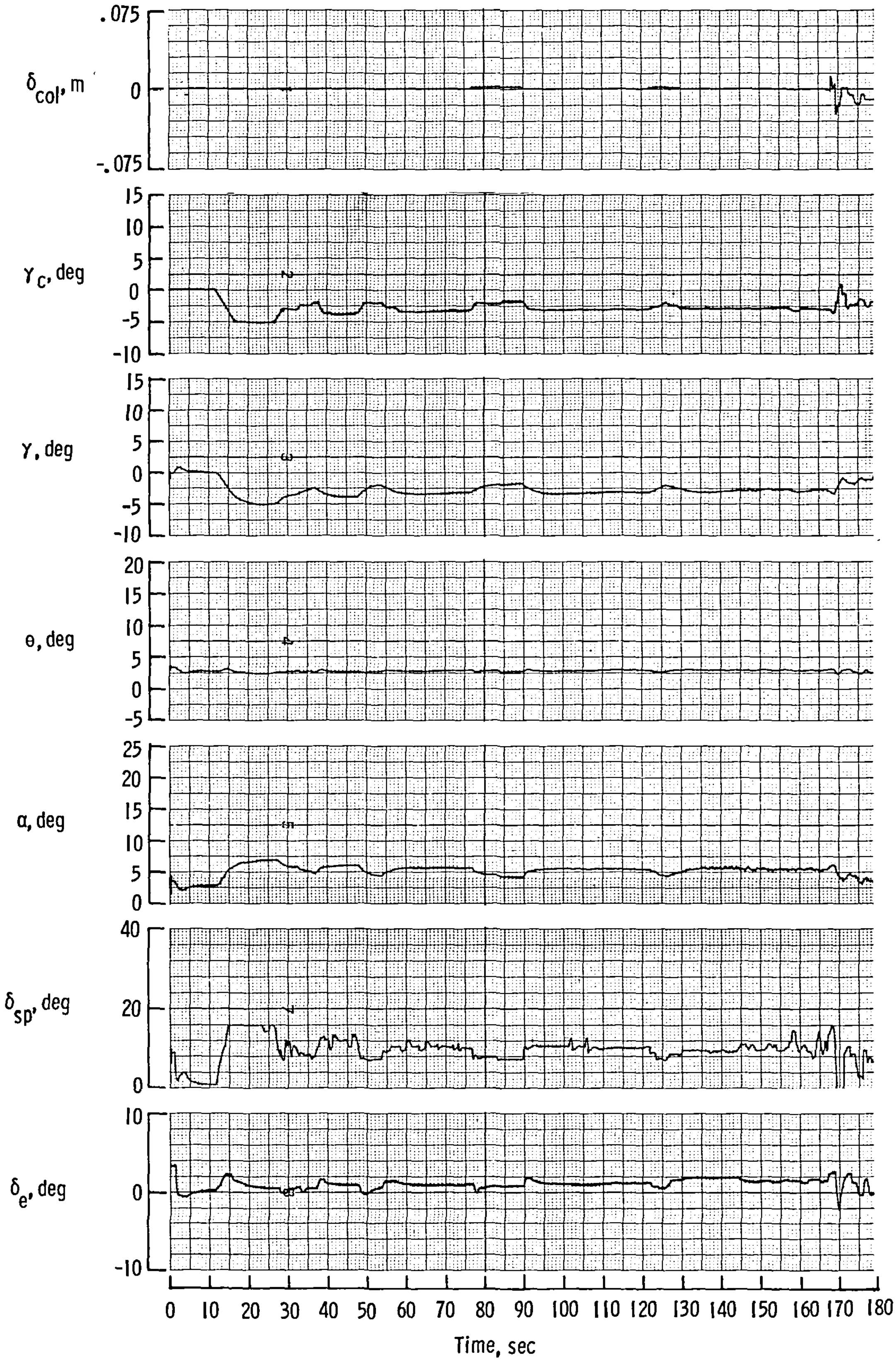

Figure 13.- Typical flight performed in light B3 wind shear with limited control authority.

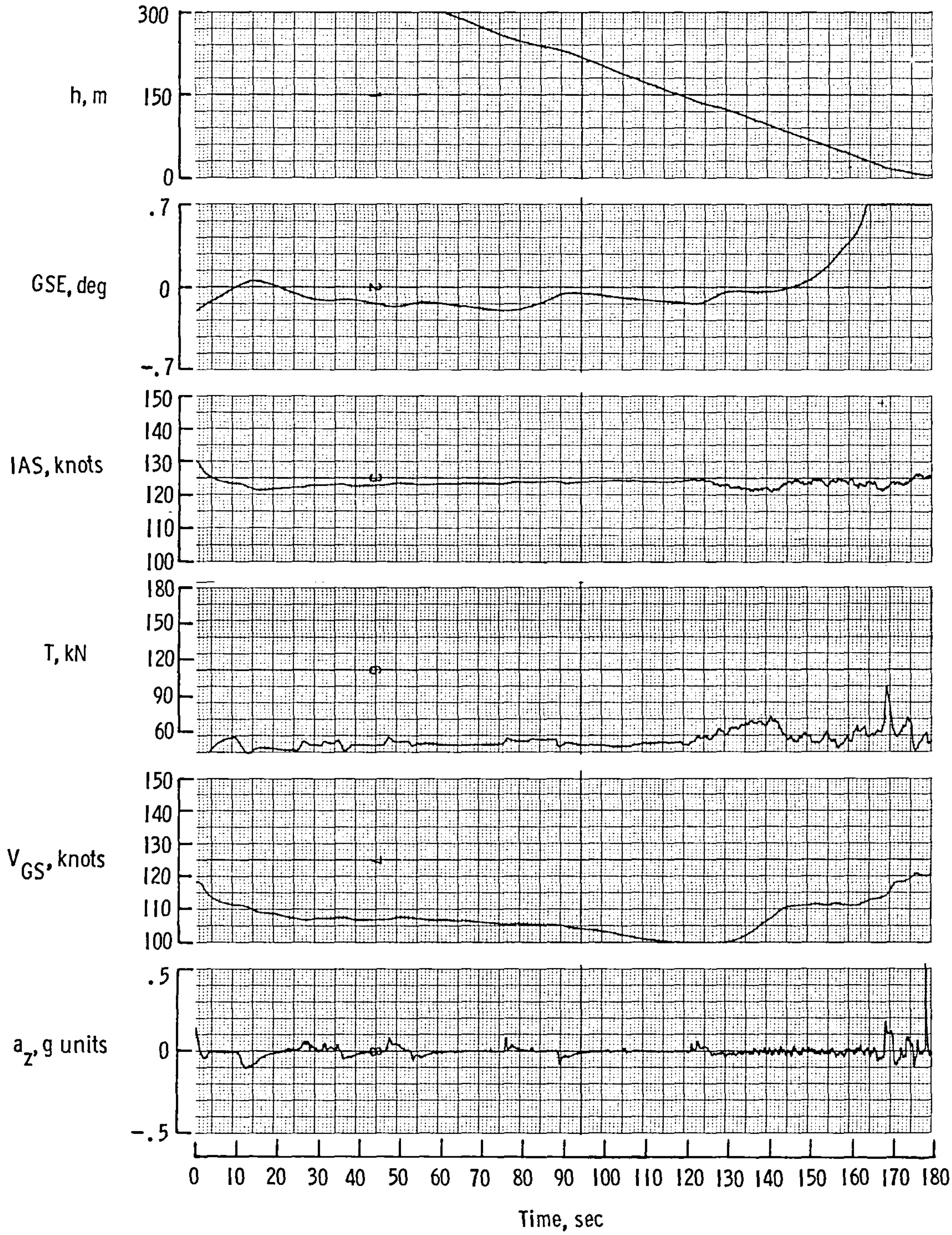

Figure 13.- Concluded.

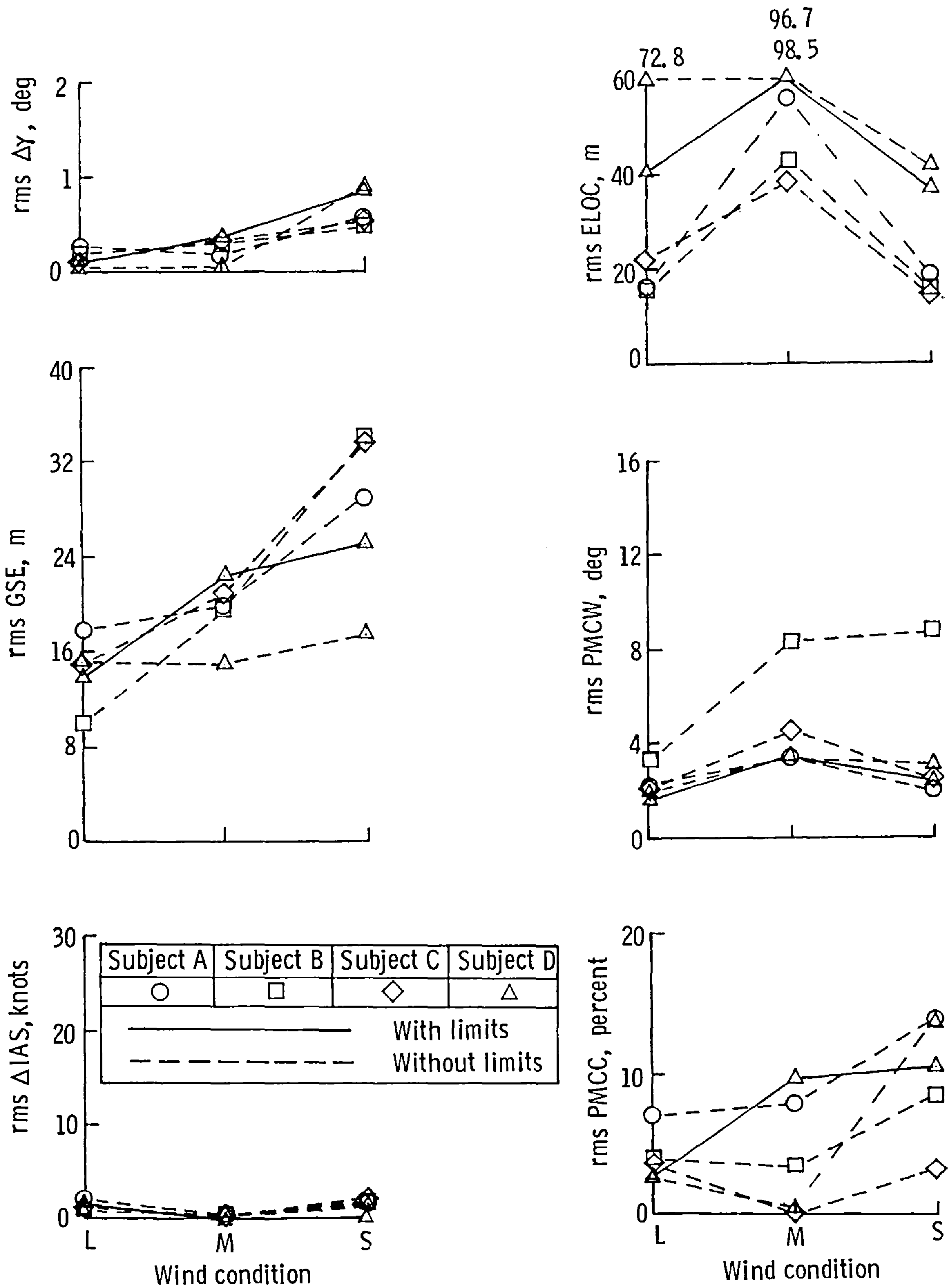

Figure 14.- Mean approach-performance parameters at altitudes between 457.2 m and 228.0 m. The symbols L, M, and S denote light, moderate, and severe winds, respectively, in this and subsequent figures.

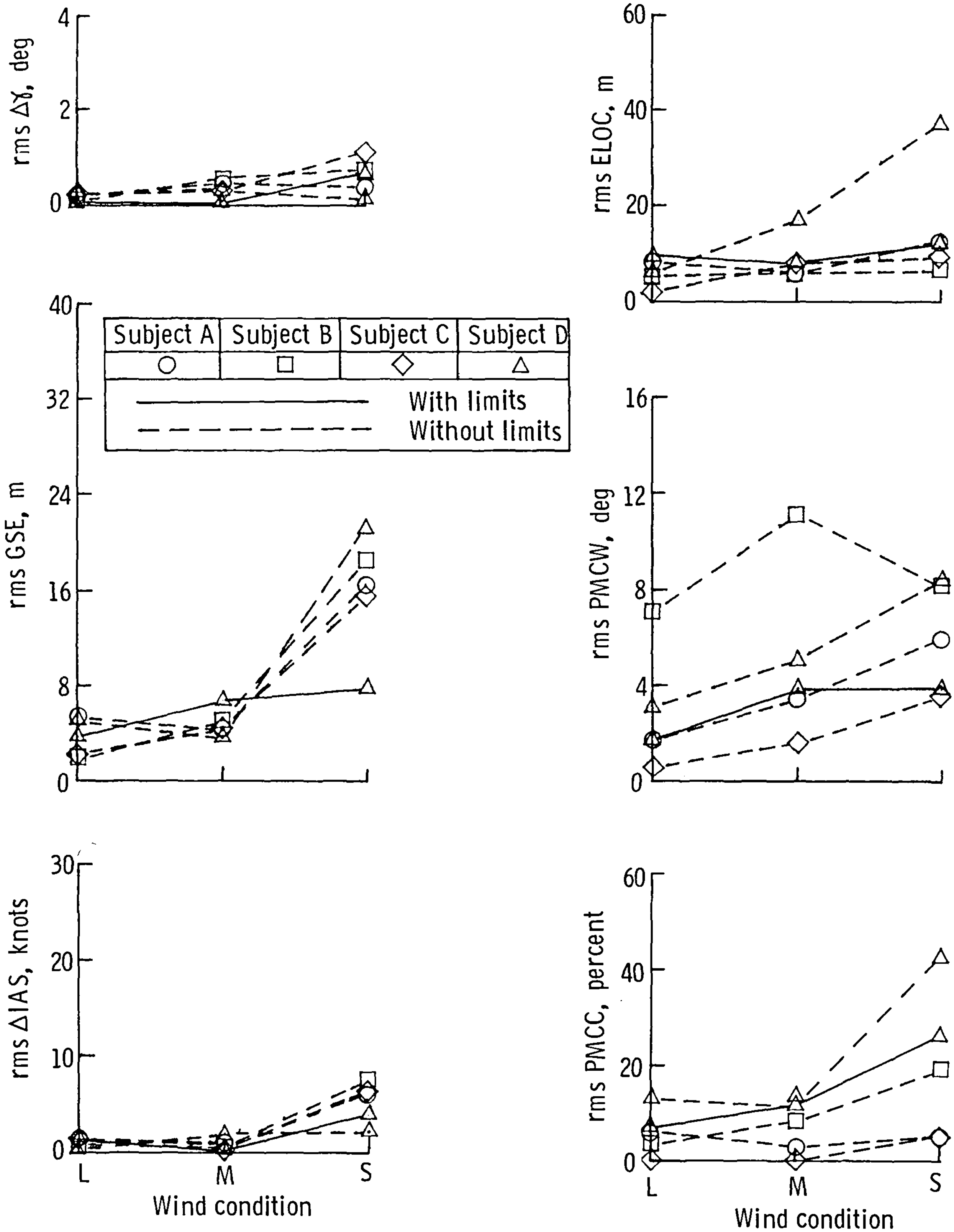

Figure 15.- Mean approach-performance parameters at altitudes between 76.2 m and 30.5 m.

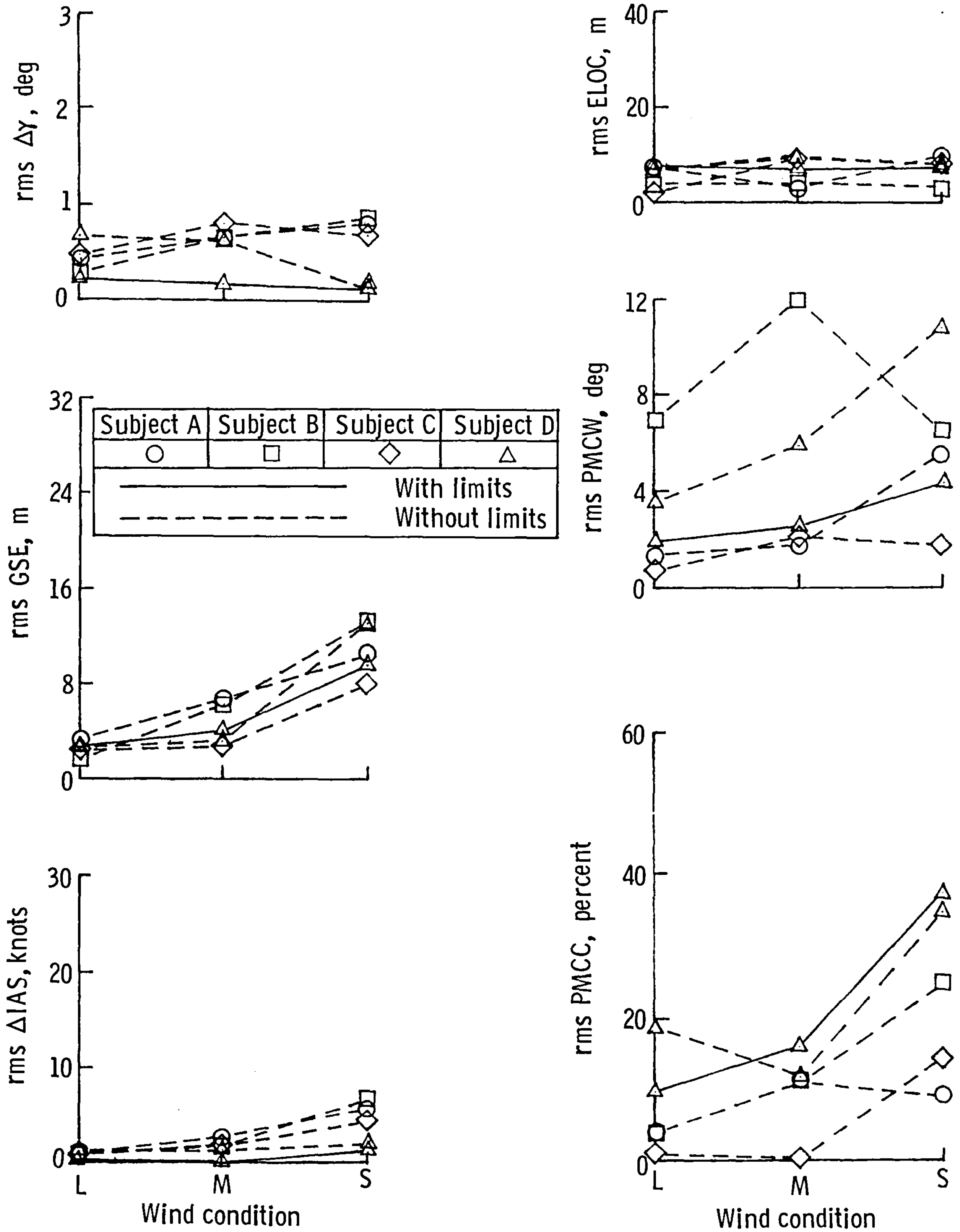

Figure 16.- Mean approach-performance parameters at altitudes between 30.5 m and 15.1 m.

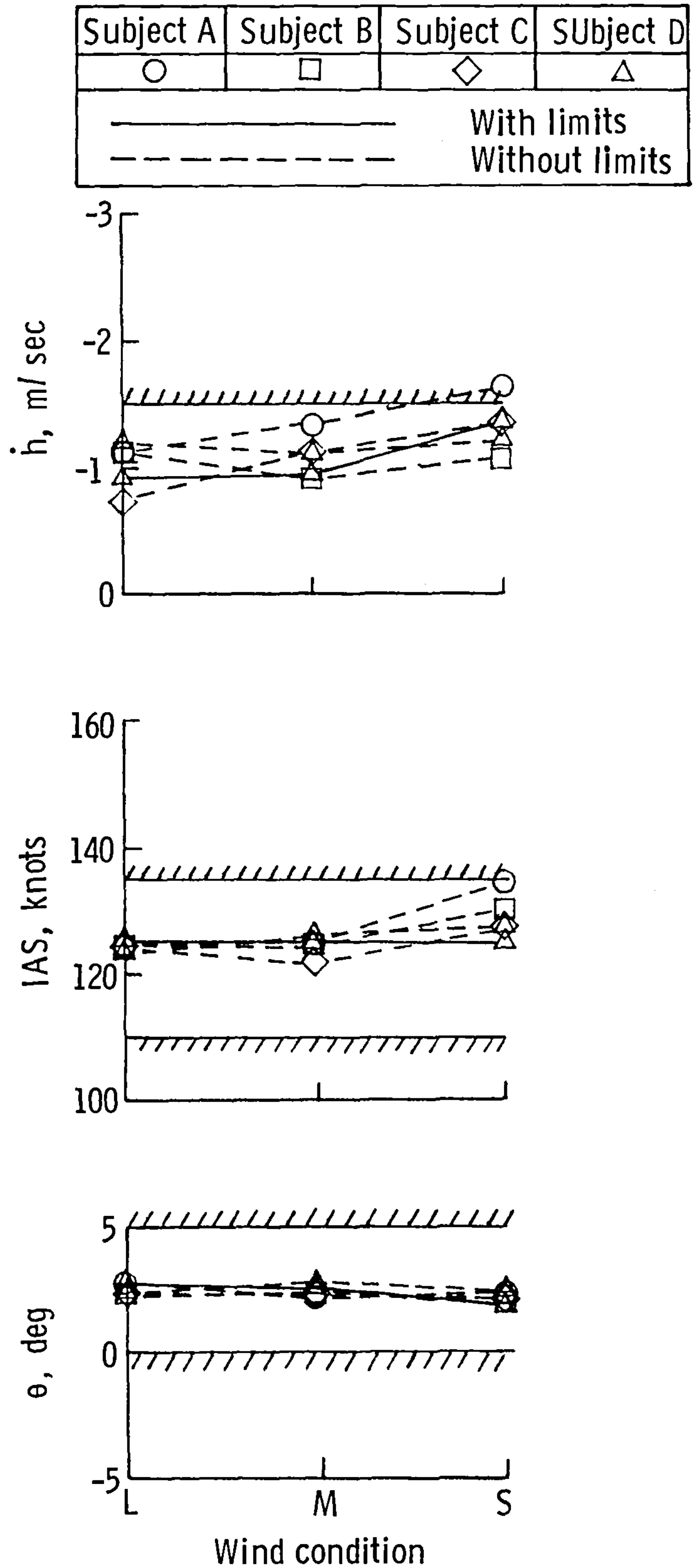

Figure 17.- Mean touchdown-performance parameters. Limits denoted by hatched lines are defined in reference 4.

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15. Supplementary Notes

16. Abstract

The effect of reduced control authority, both in symmetric spoiler travel and thrust level, on the effectiveness of a decoupled longitudinal control system is examined during the approach and landing of the NASA Terminal Configured Vehicle (TCV) Aft Flight Deck Simulator in the presence of wind shear. The evaluation was conducted in a fixed-base simulator that represented the TCV aft cockpit. There were no statistically significant effects of reduced spoiler and thrust authority on pilot performance during approach and landing. Increased wind severity degraded approach and landing performance by an amount that was often significant. However, every attempted landing was completed safely regardless of the wind severity. There were statistically significant differences in performance between subjects, but the differences were generally restricted to the control wheel and control-column activity during the approach.

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